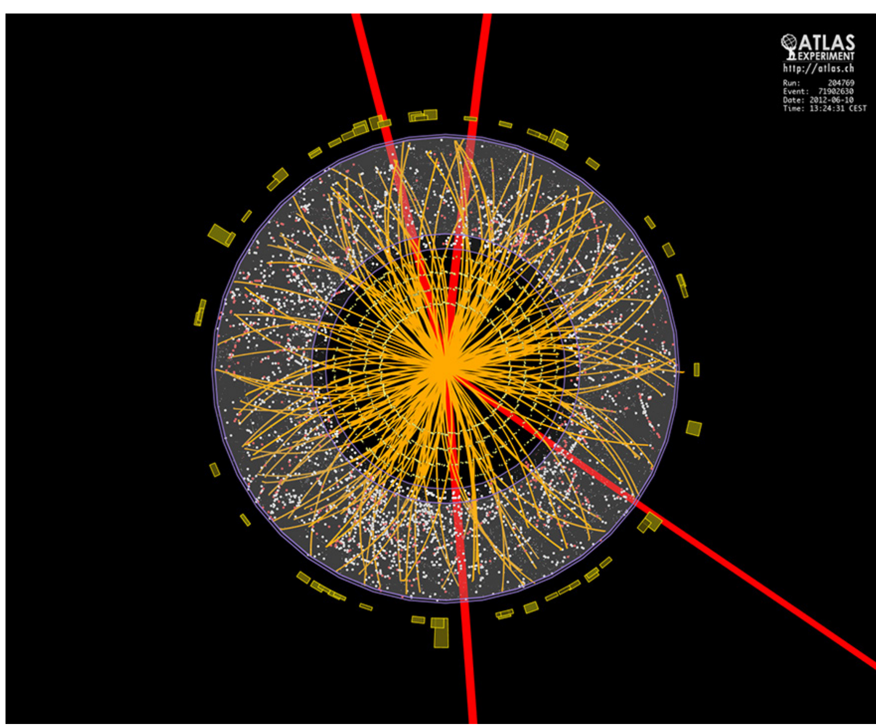
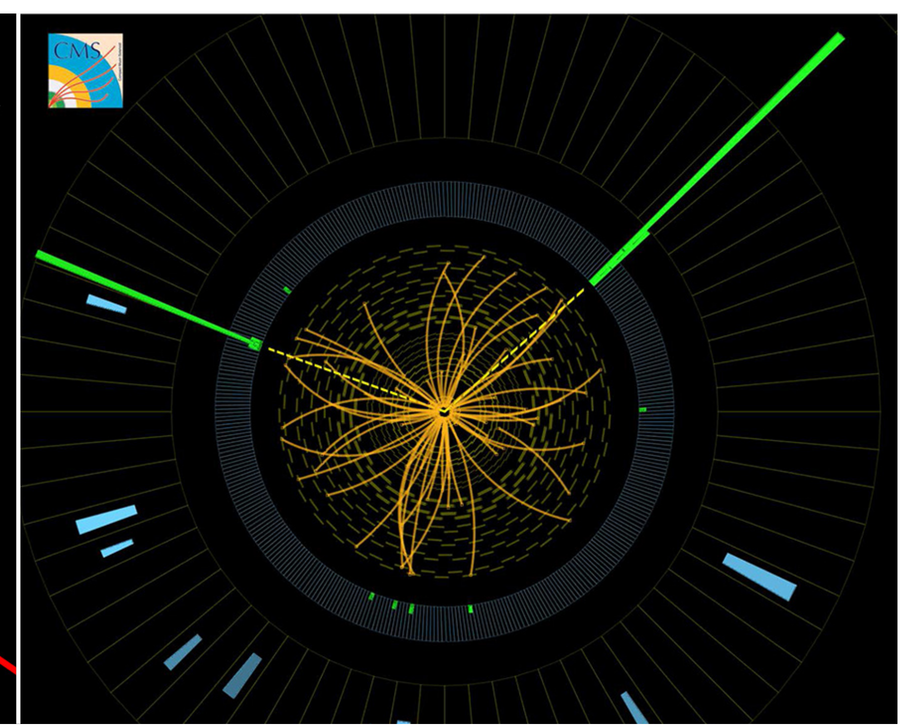
Physics opportunities at future circular colliders

Lian-Tao Wang
University of Chicago

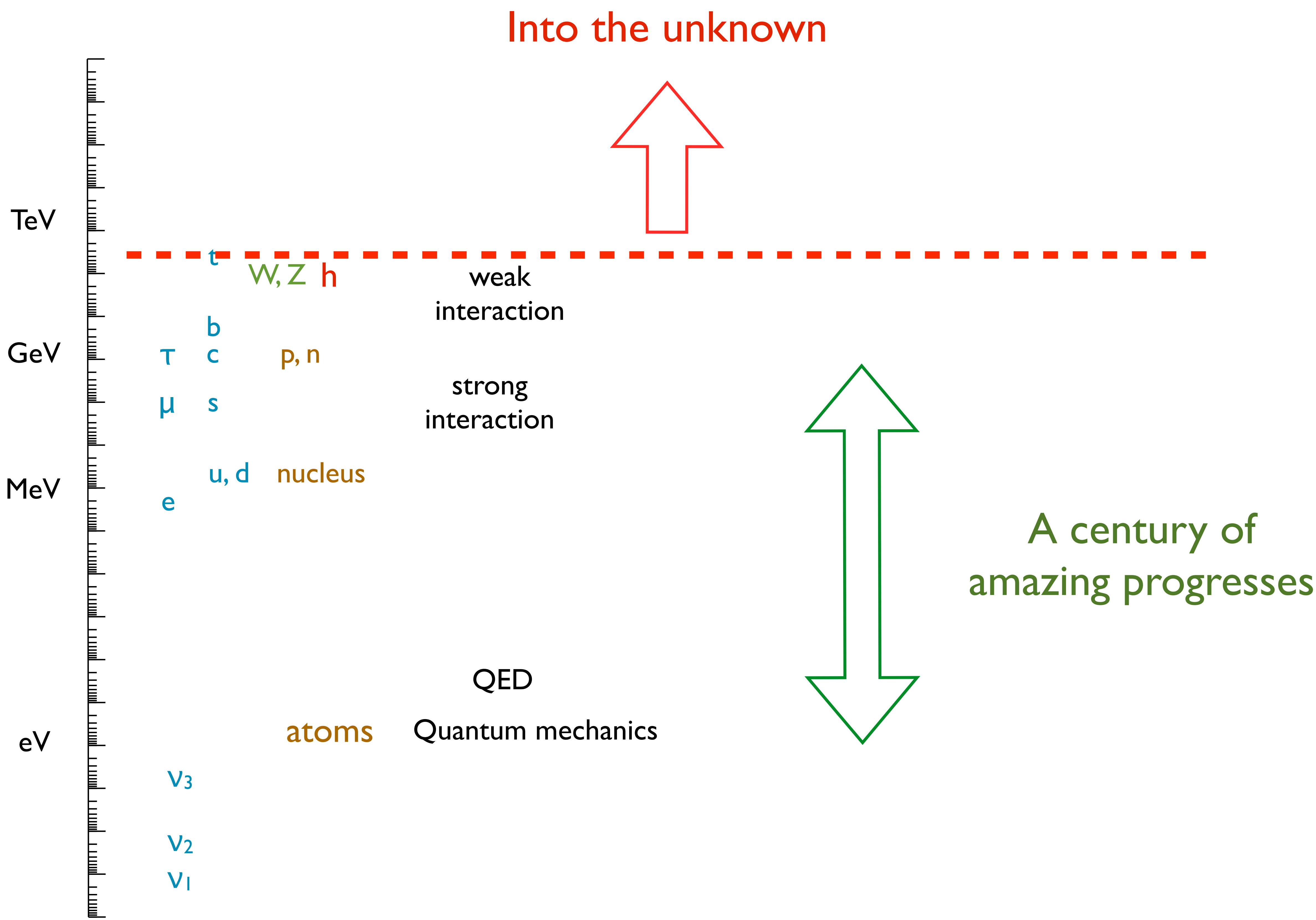
BNL, Feb 16 2016

A spectacular discovery!

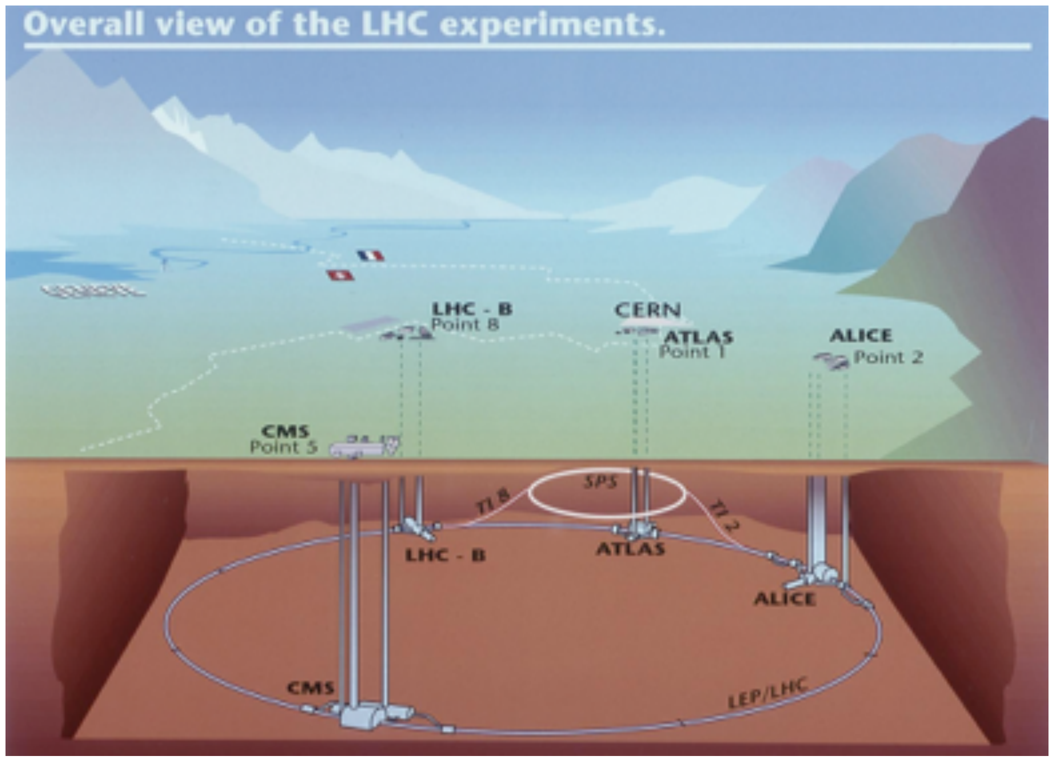


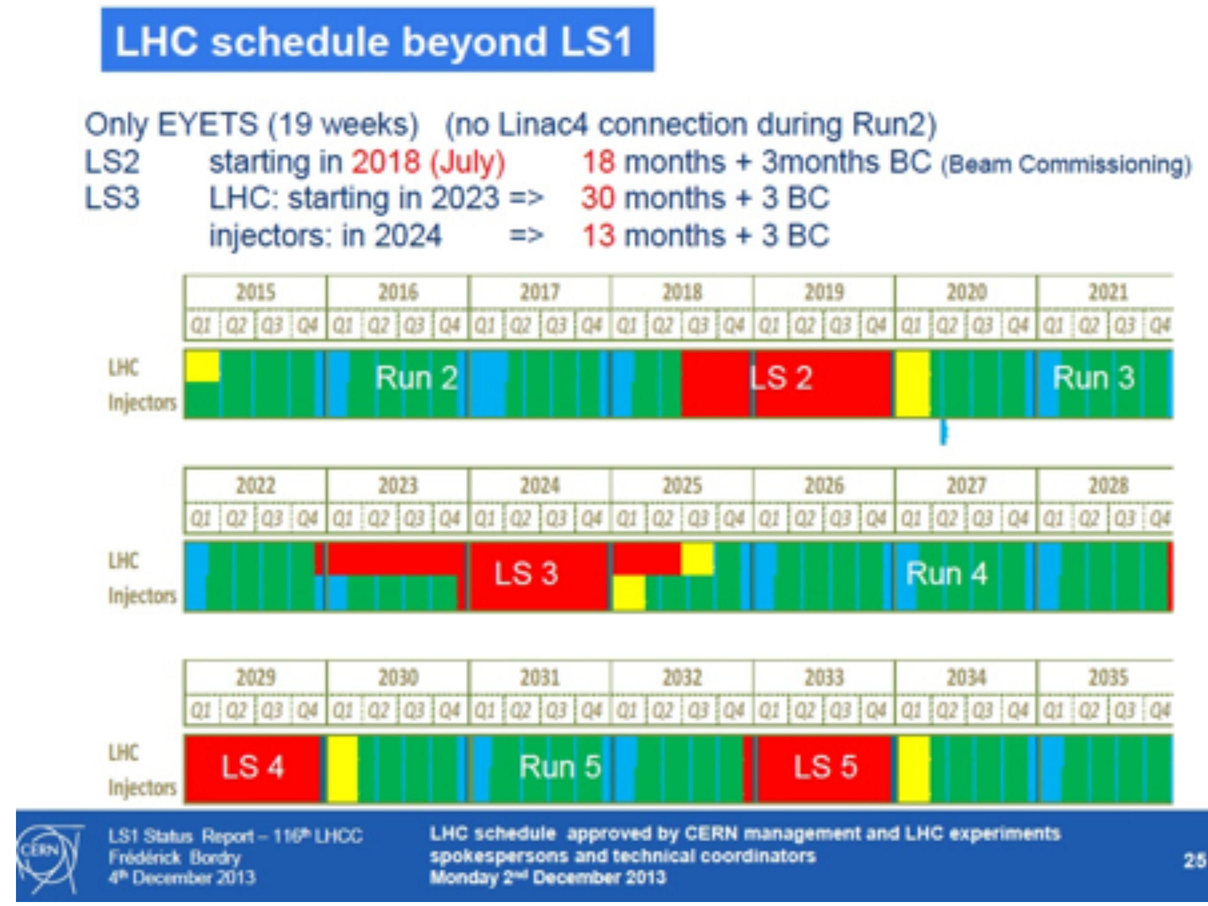


The beginning of a new era



Immediate future: Large Hadron Collider

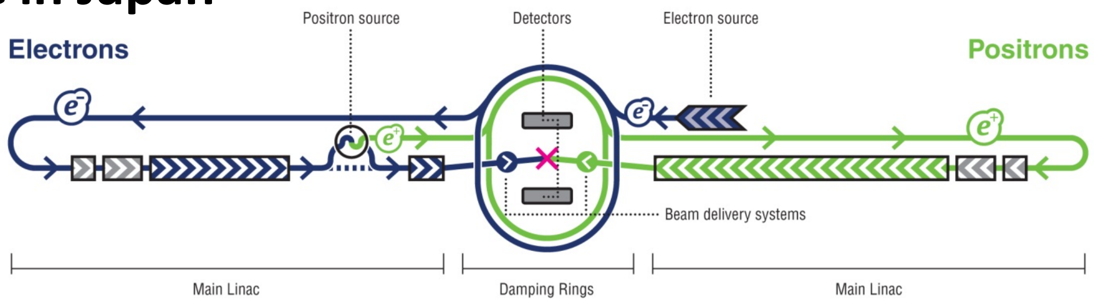




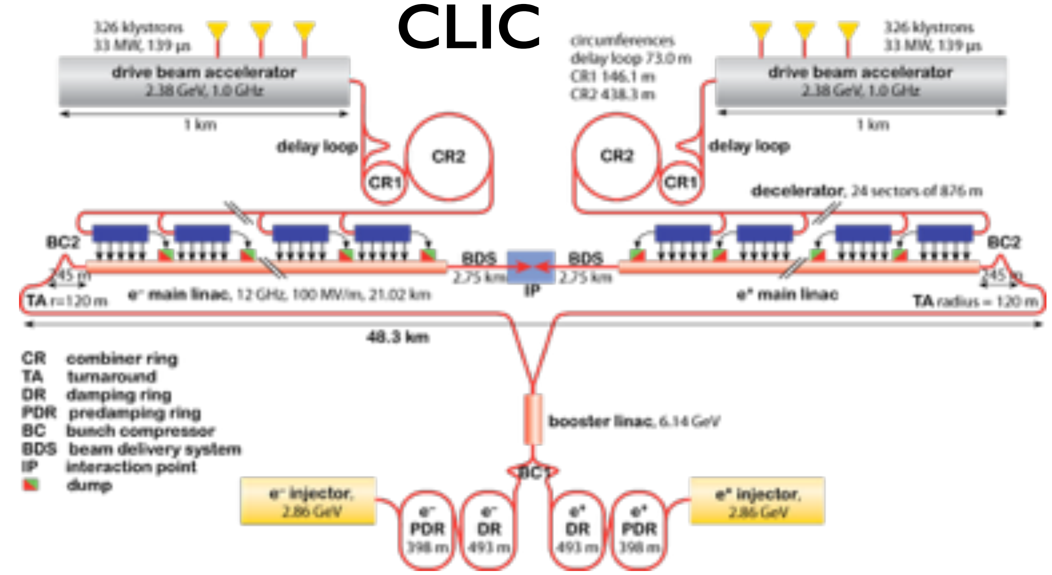
- Started this year at higher energy and intensity
  - E_{cm} = 13-14 TeV.
  - 10s and ultimately 100+ more data.

Further down the road

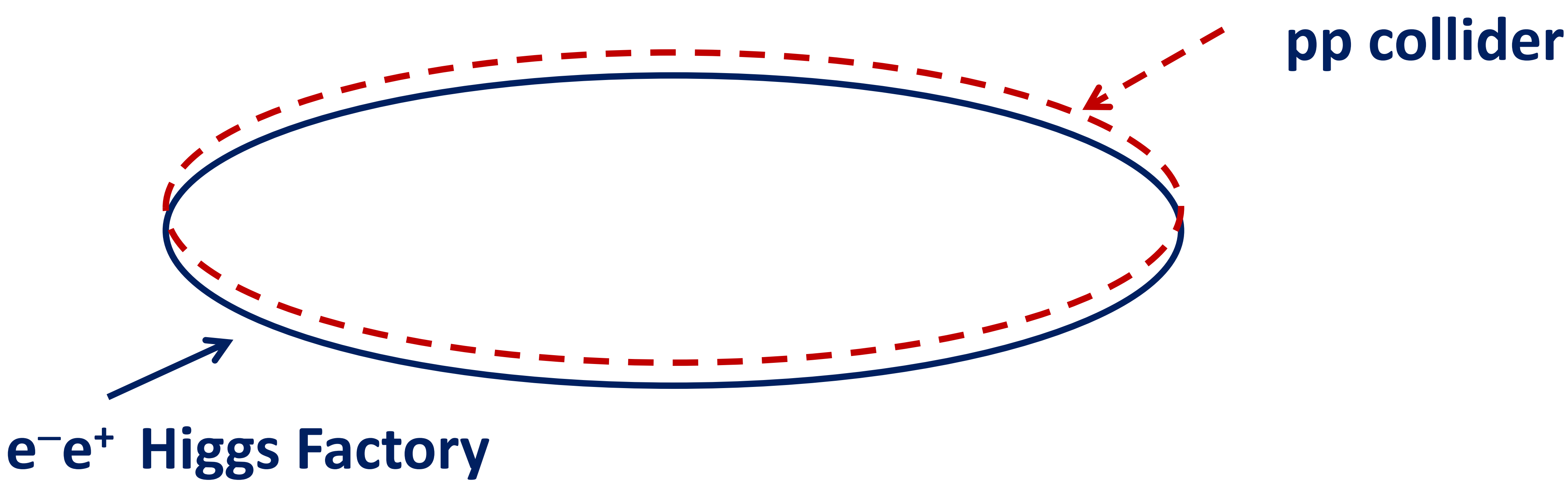
ILC in Japan



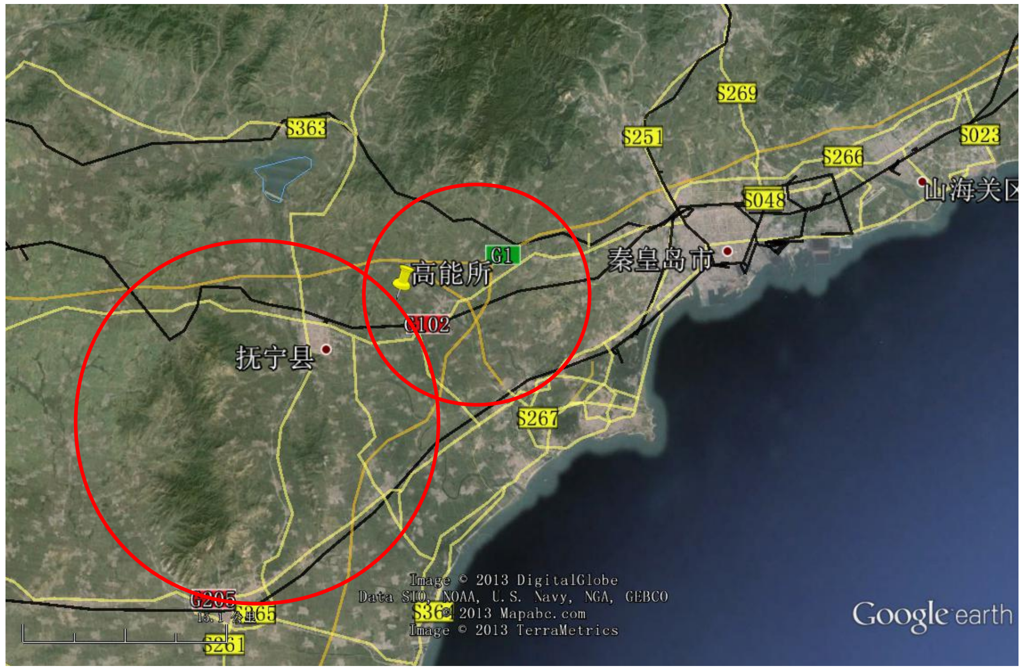
CLIC



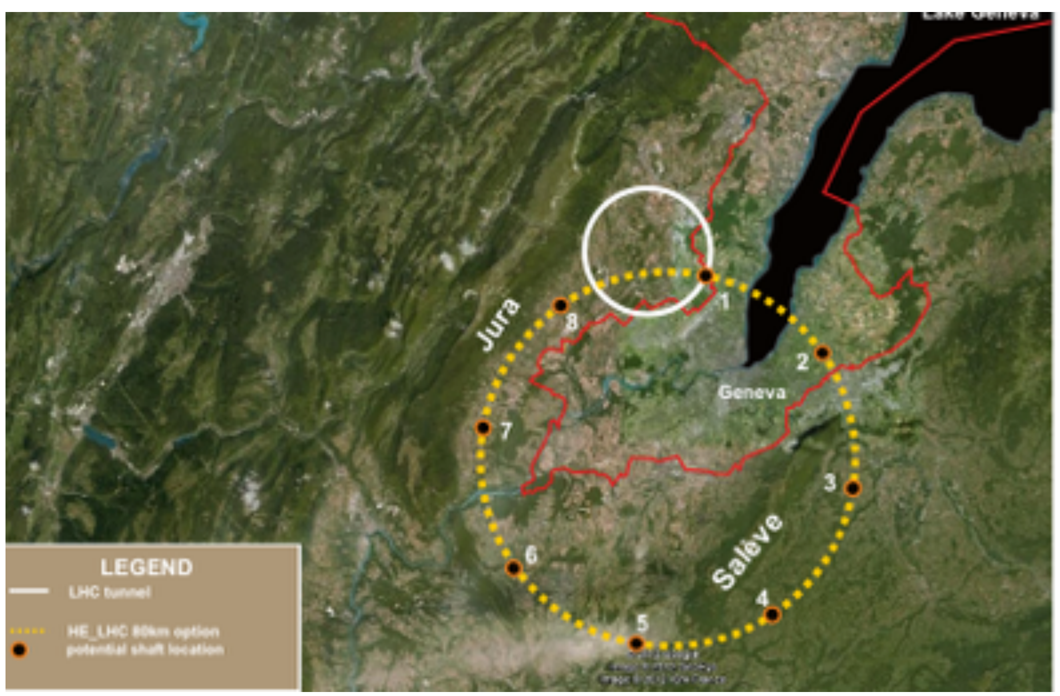
Circular. “Scale up” LEP+LHC



Future circular colliders



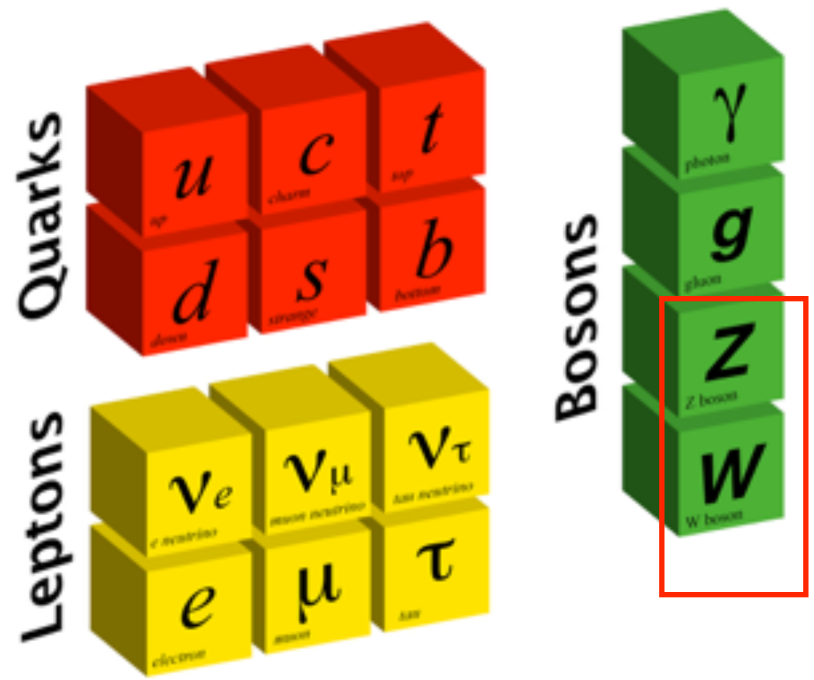
China.
Higgs factory: CEPC
pp Collider: SppC



CERN
Higgs factory: FCC-ee
pp Collider: FCC-hh

So, what are we looking for?

The Standard Model before 2012



$$m_{\mathrm{W,Z}} \simeq 10^2\ \mathrm{GeV}$$

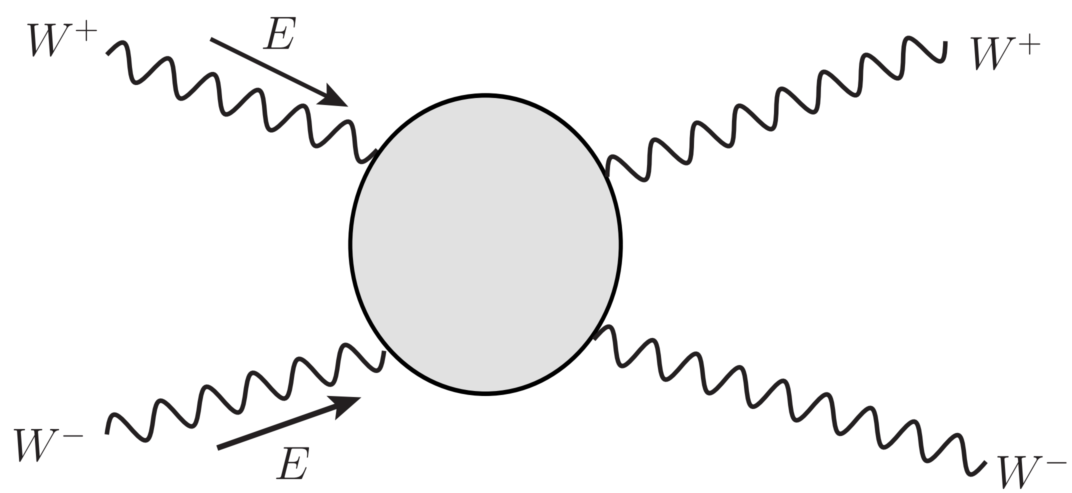
- Electroweak symmetry breaking (EWSB).
  - Weak interaction has finite range

$$V_{\mathrm{weak}}(r) \approx \frac{e^{-r/r_{\mathrm{W}}}}{r},\ r_{\mathrm{W}} \approx m_{\mathrm{W,Z}}^{-1} \approx 10^{-17}\ \mathrm{m}$$

Fermi, 1934

But, still need something else.

Consider:



$$\text{Amplitude} \approx g_{\rm W}^2 \frac{E^2}{m_{\rm W}^2}$$

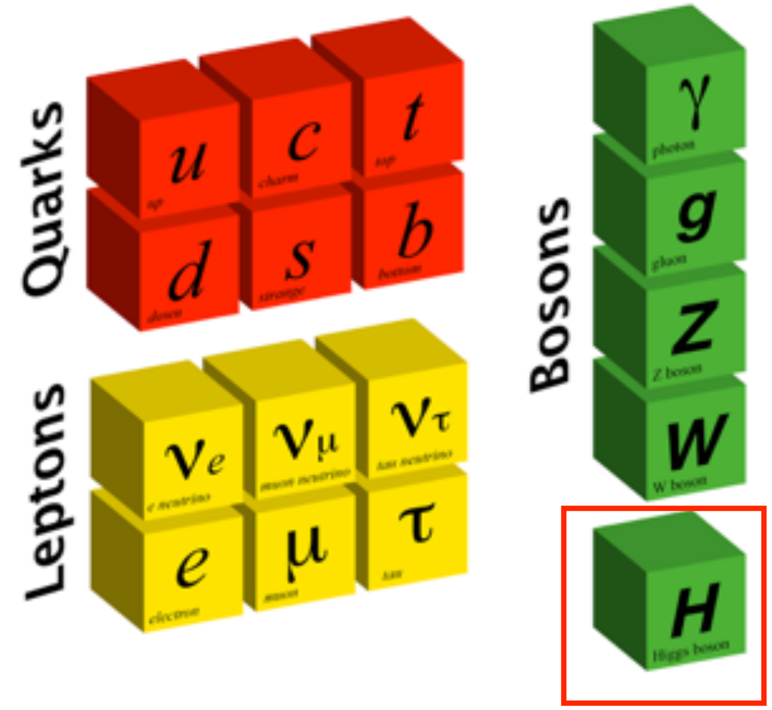
Growing stronger at higher energy.
Perturbative unitarity breaks down.

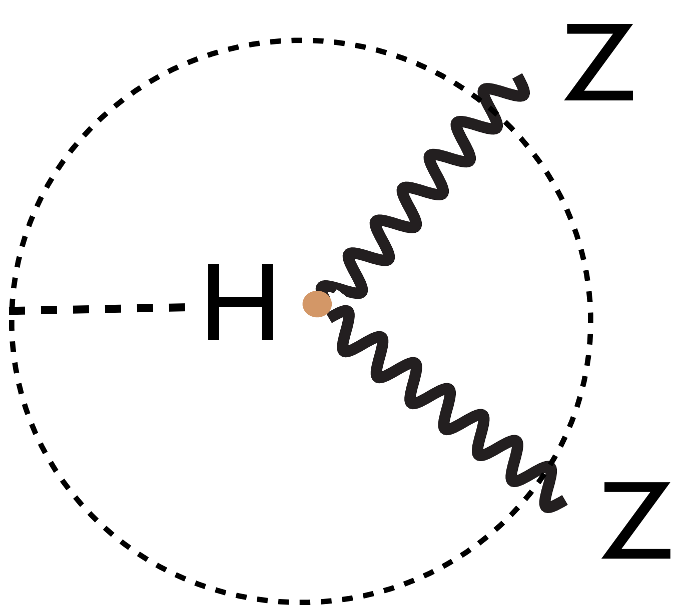
- Therefore, this picture is not valid at $E \sim 4\pi m_{\rm W}/g_{\rm W} \simeq \ \text{TeV}$
- Something new must happen before TeV scale.

The answer

- The Higgs boson.
  - Spin 0 (scalar)

- Higgs field gives masses to electrons, W/Z....





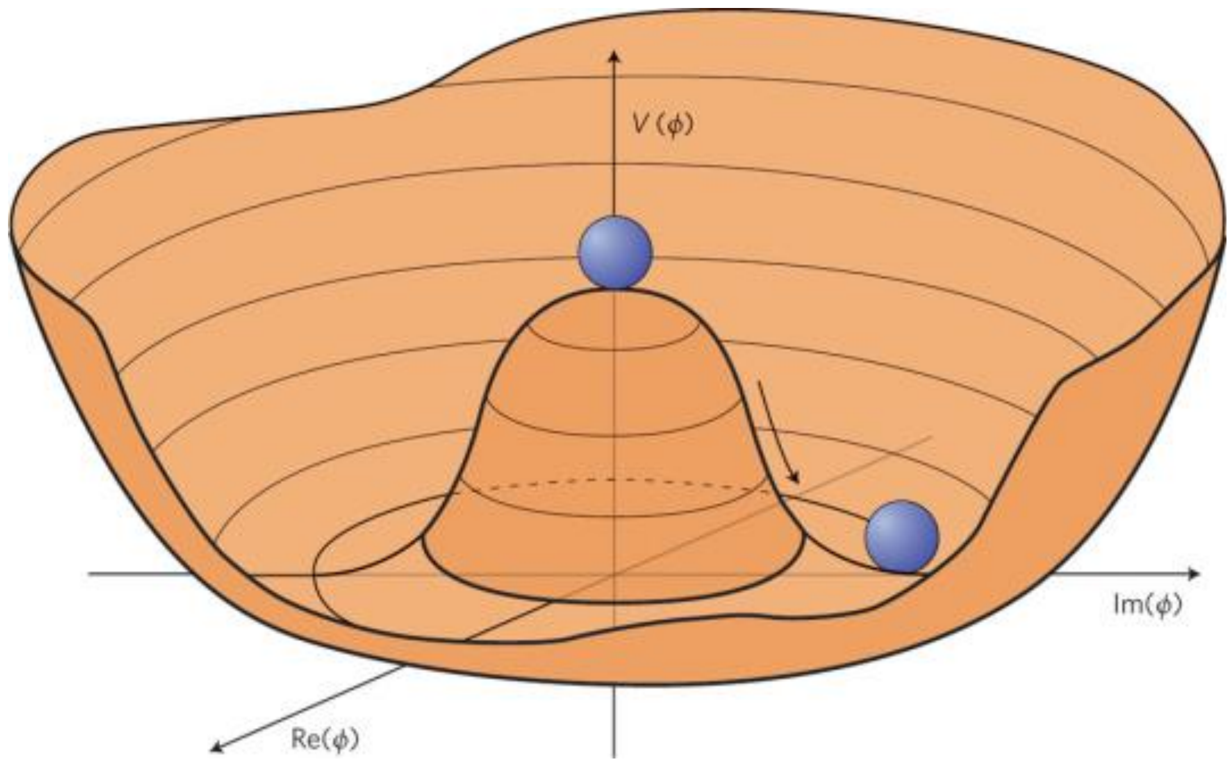
Understanding the Higgs

Why is Higgs puzzling?

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

"Simple" picture: Mexican hat



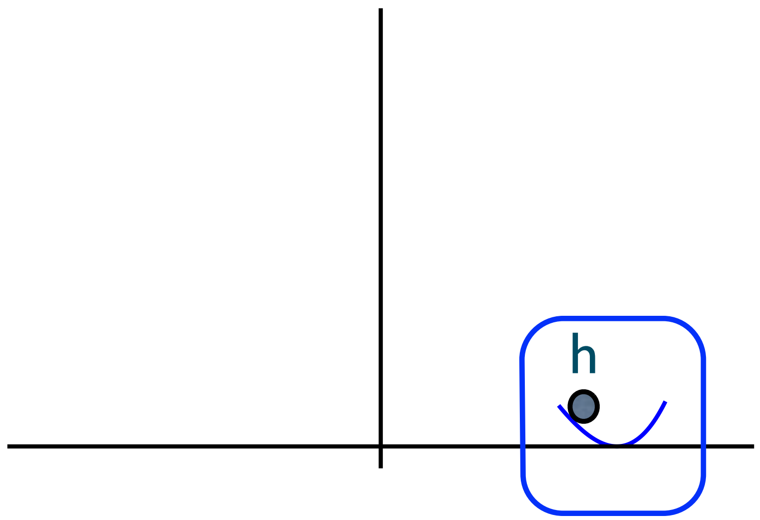
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

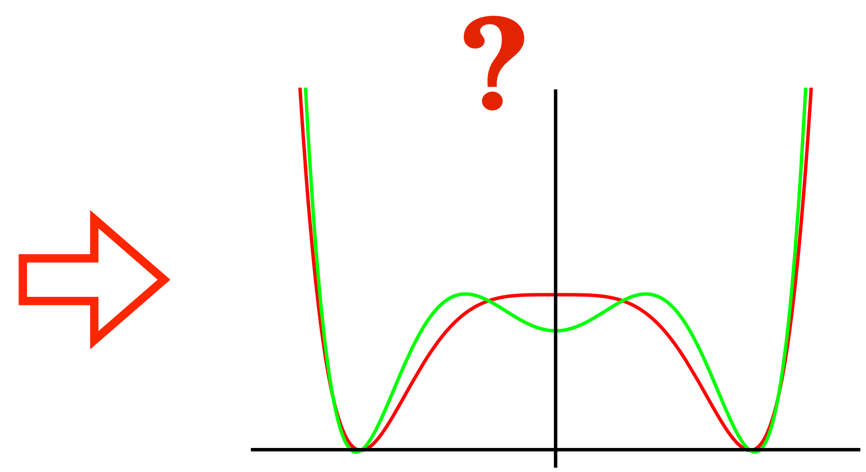
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

However, this simplicity is deceiving.
Parameters not predicted by theory. Can not be the complete picture.

Not even sure about "Mexican hat".



What we know now



$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

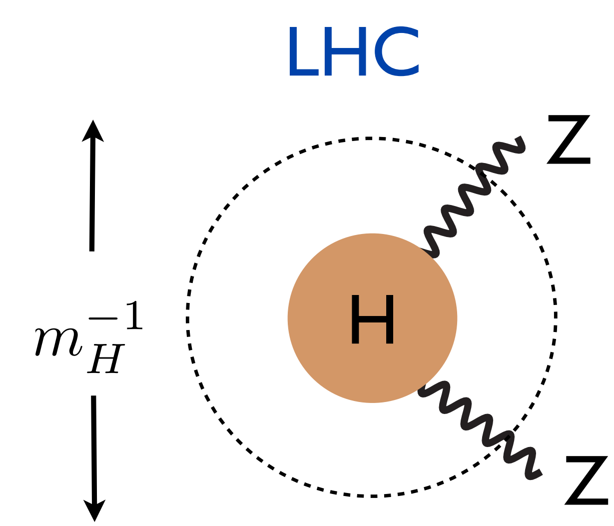
Is the EW phase transition first order?

Where do we start?

Is Higgs really the simple elementary particle?
Or, is it something more complicated?

Visualize as the "size" of the particle
Complicated: size = mass^{-1} (just like proton)
Simple: point-like

Why it might be complicated? An example:
Landau-Ginzburg replaced by BCS, more complicated!



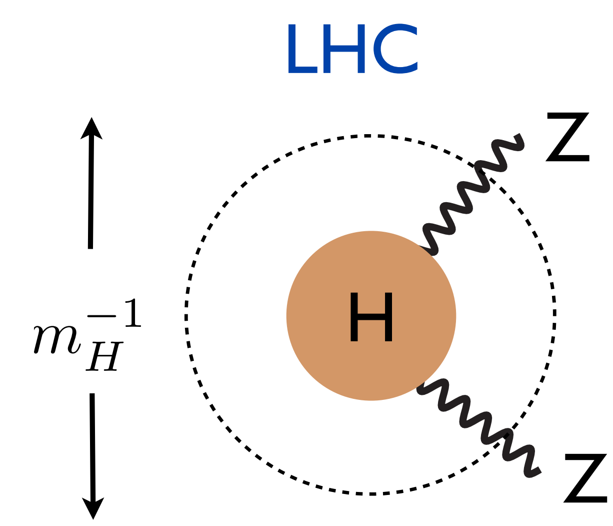
LHC results so far: point like, "sort of",
but not conclusive.

Need to look at couplings in greater detail.

How well do we need to know?

In general, the deviation from the simple picture can be parameterized as

$$\delta = c\frac{m_W^2}{M_{\rm NP}^2},\ \ c = \mathcal{O}(1)$$



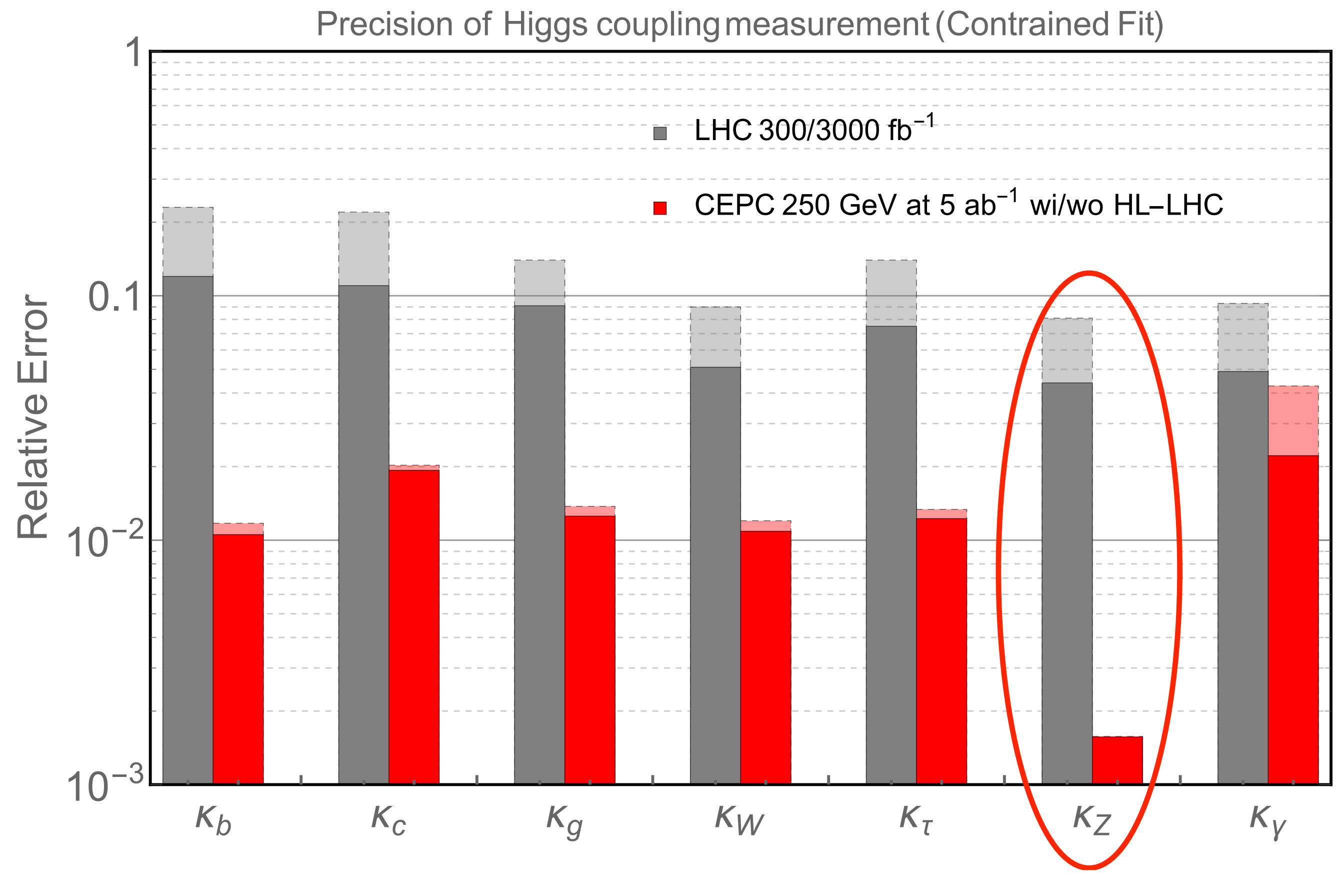
LHC will measure the Higgs property down to several percent, probing $M_{NP} \lesssim$ TeV.

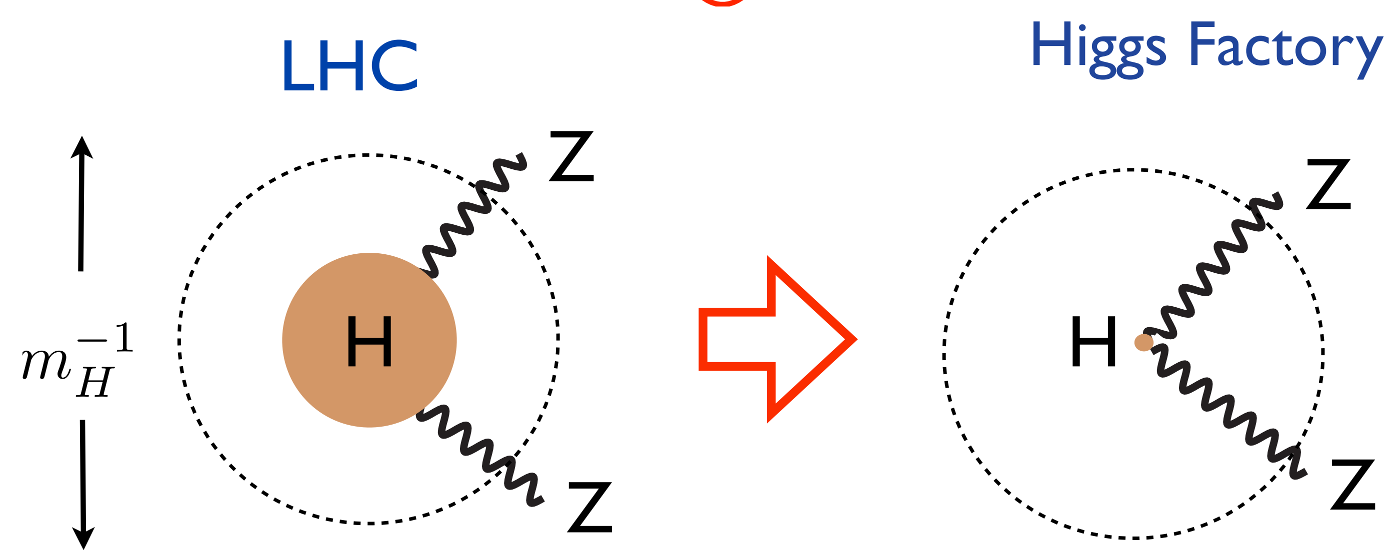
It will also search new physics particles directly with mass $M_{NP} \lesssim$ TeV.

To be comparable or go beyond, need to measure Higgs coupling to % level or better

How well can we do?

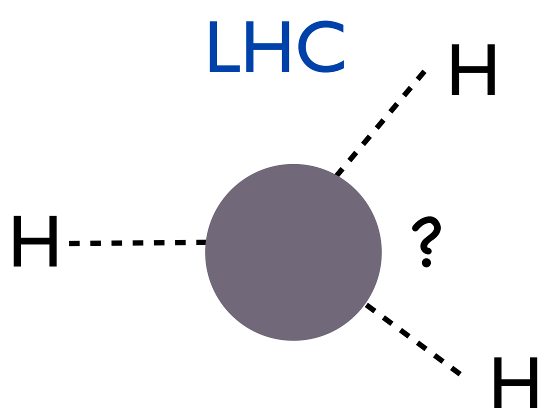
$$\kappa_Z = \frac{g_{hZ}(\text{Measured})}{g_{hZ}(\text{SM})}$$





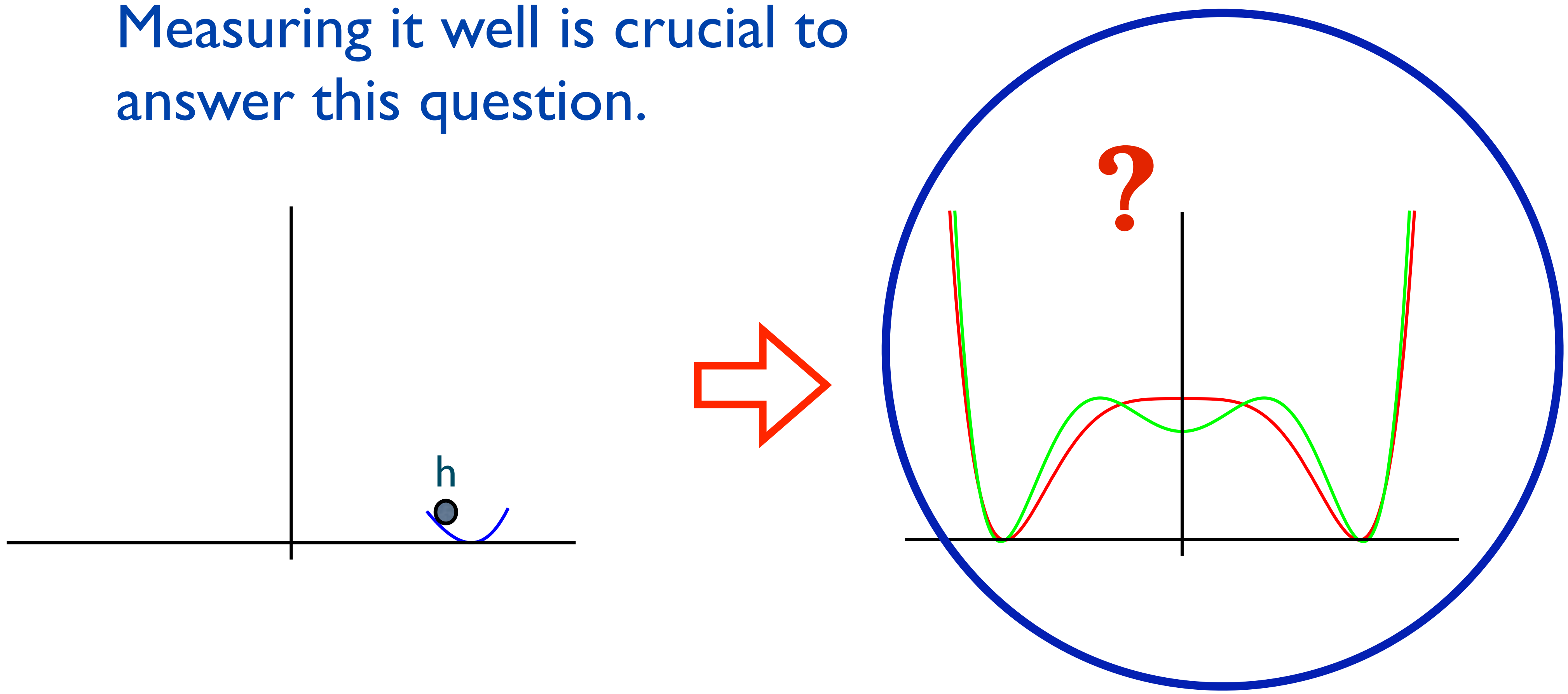
Higgs factory has what it takes!

Self coupling



Unique type of coupling for spin-0 scalars
Not seen before in nature!

Measuring it well is crucial to answer this question.

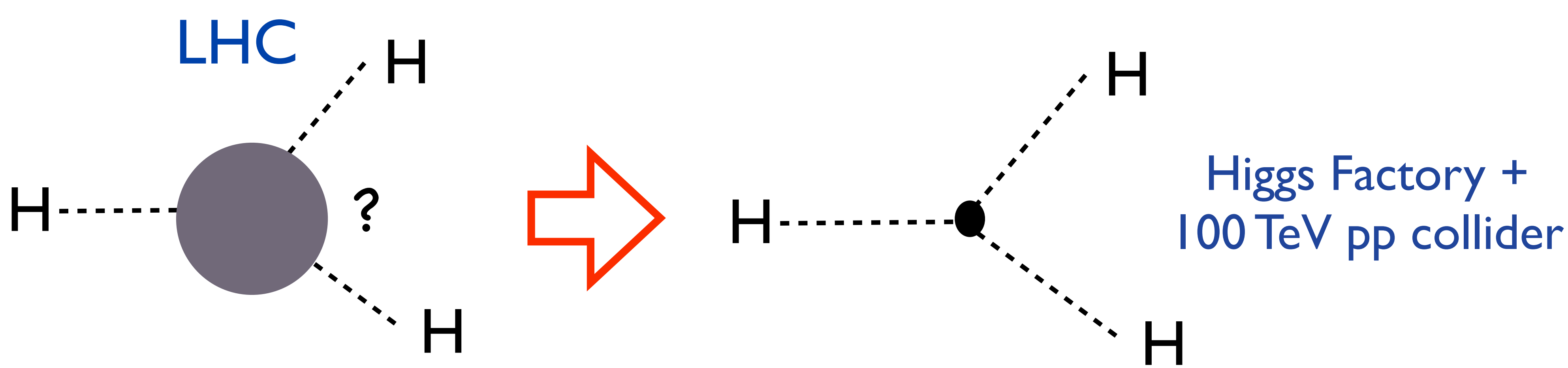


Measuring Higgs self coupling

Triple Higgs coupling at 100 TeV pp collider
30 ab^{-1}

$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh+\text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh+\text{jet} \end{cases}$$

Barr, Dolan, Englert, de Lima, Spannowsky



More difficult, but doable.

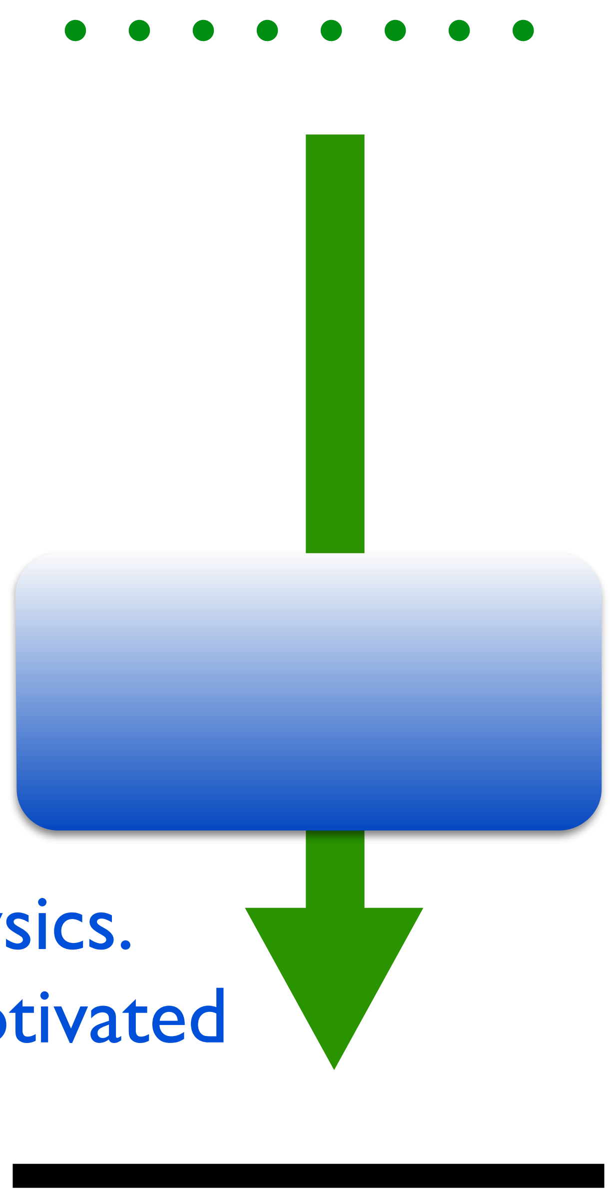
Beyond the Higgs

New circular colliders with unprecedented energy reach and precision.

Greatly enhance the search for new physics, help answer fundamental questions.

Examples: naturalness, dark matter, …

Naturalness of electroweak symmetry breaking



Λ: a cut-off.
The energy scale of new physics
responsible for EWSB

What is Λ? Can it be very high,
such as $M_{Planck} = 10^{19}$ GeV, ...?

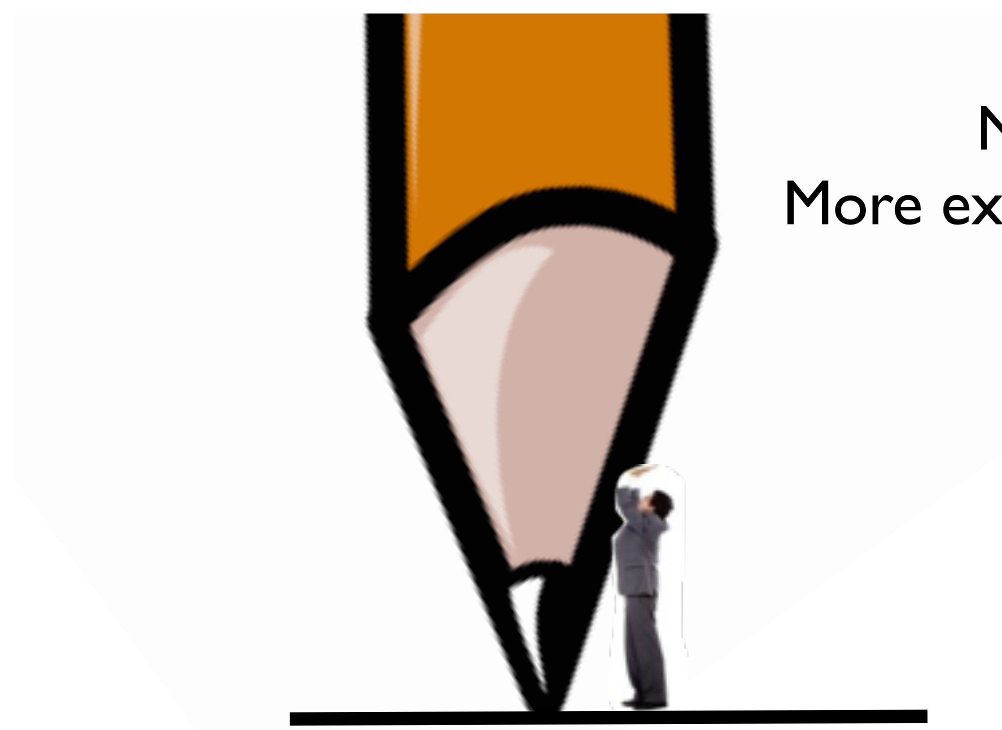
If so, why is so different from 100 GeV?

TeV new physics.
Naturalness motivated

Electroweak scale, 100 GeV.
m_h , m_W ...

Is fine-tuning ok?

- Mathematically, yes.
  Can always solve $m_h^2(\text{physical}) = m_0^2 + c\ \Lambda^2$.   But...

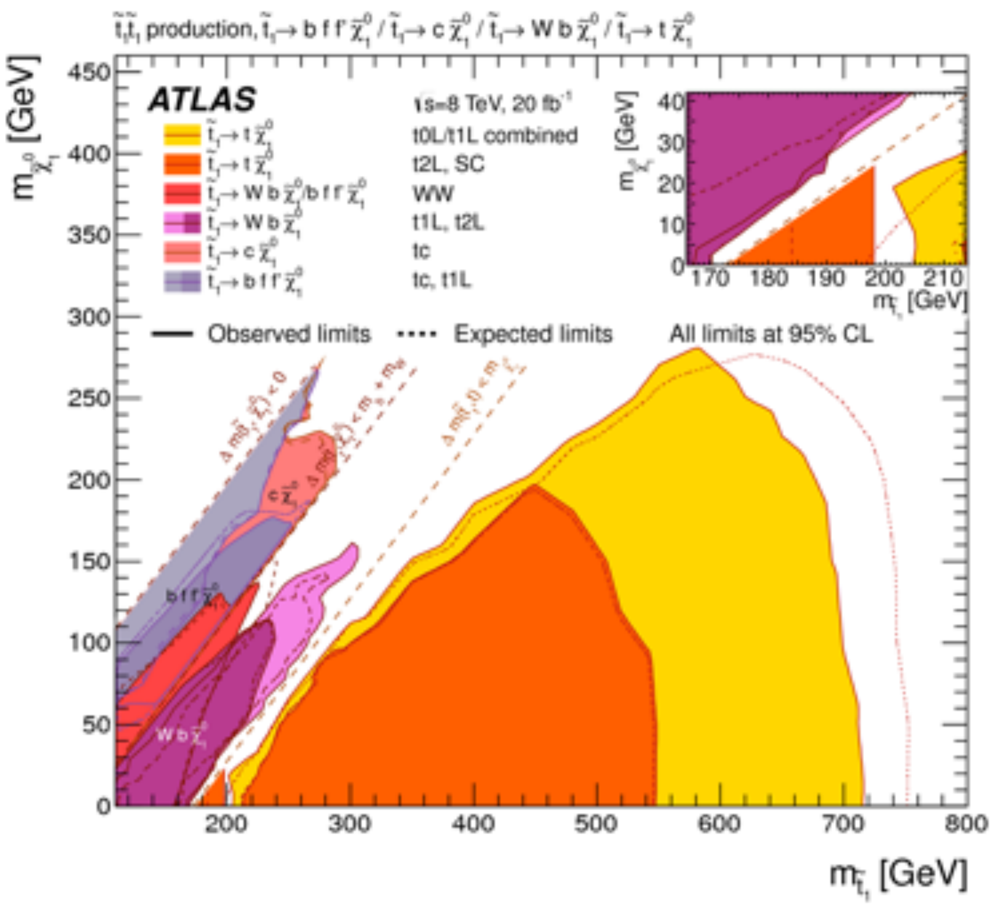


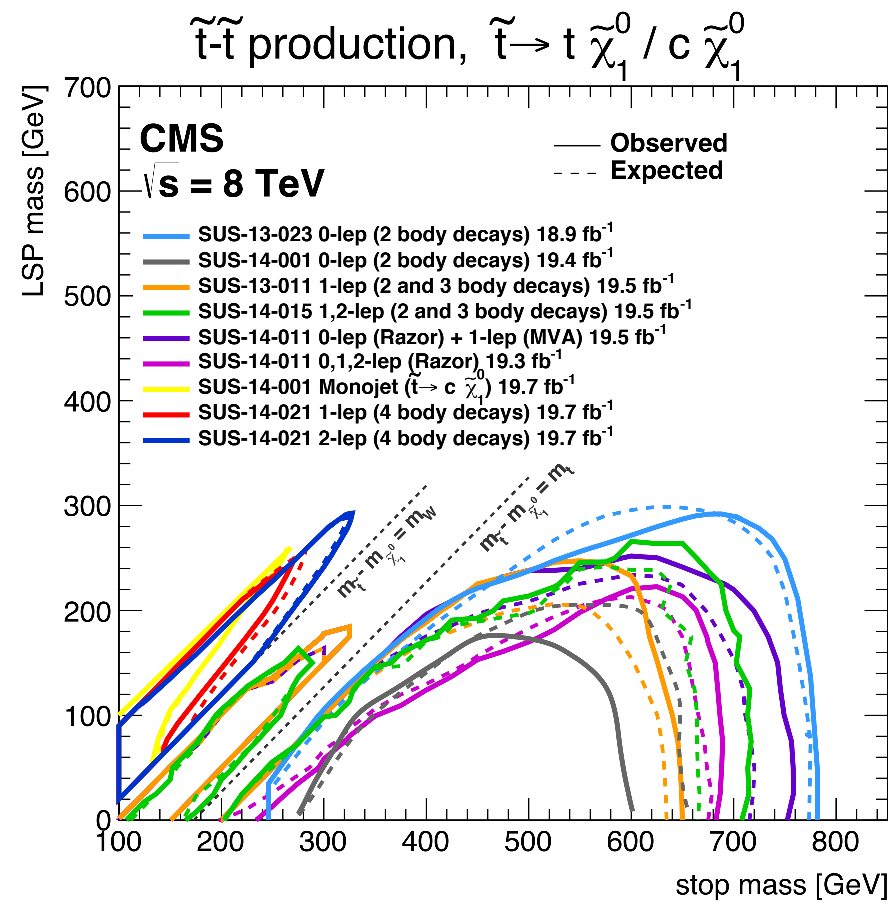
No rope?
More exotic possibilities

Similarly, we have been searching for an explanation for the fine-tuning of Higgs mass $O(10^{-32})$

Another fine-tuning problem

TeV new physics: SUSY stop



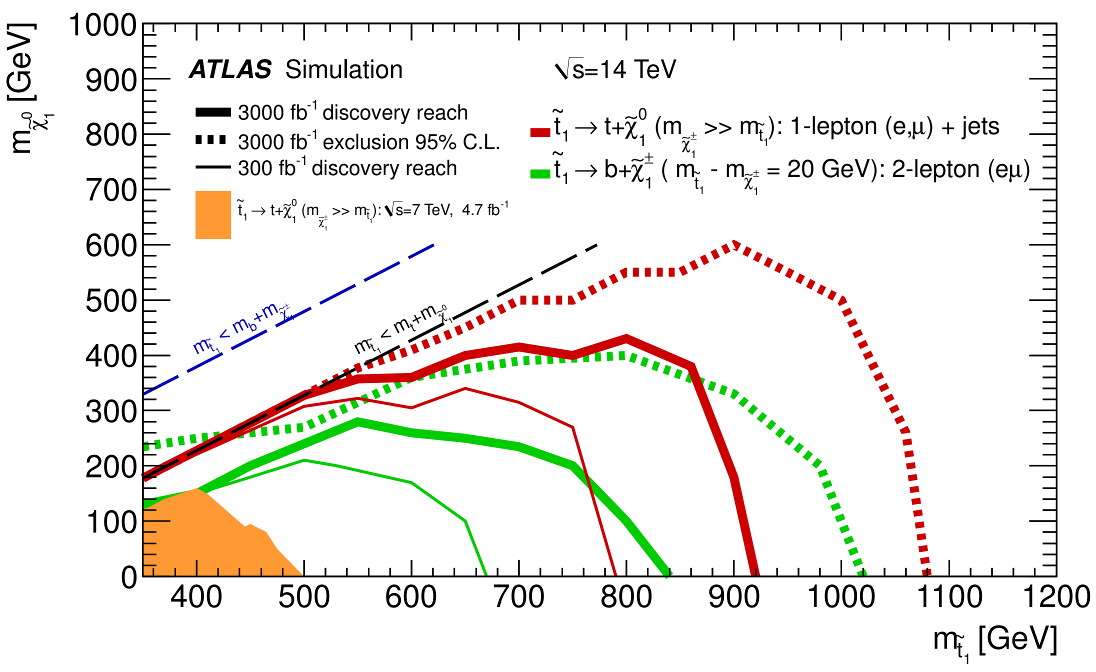


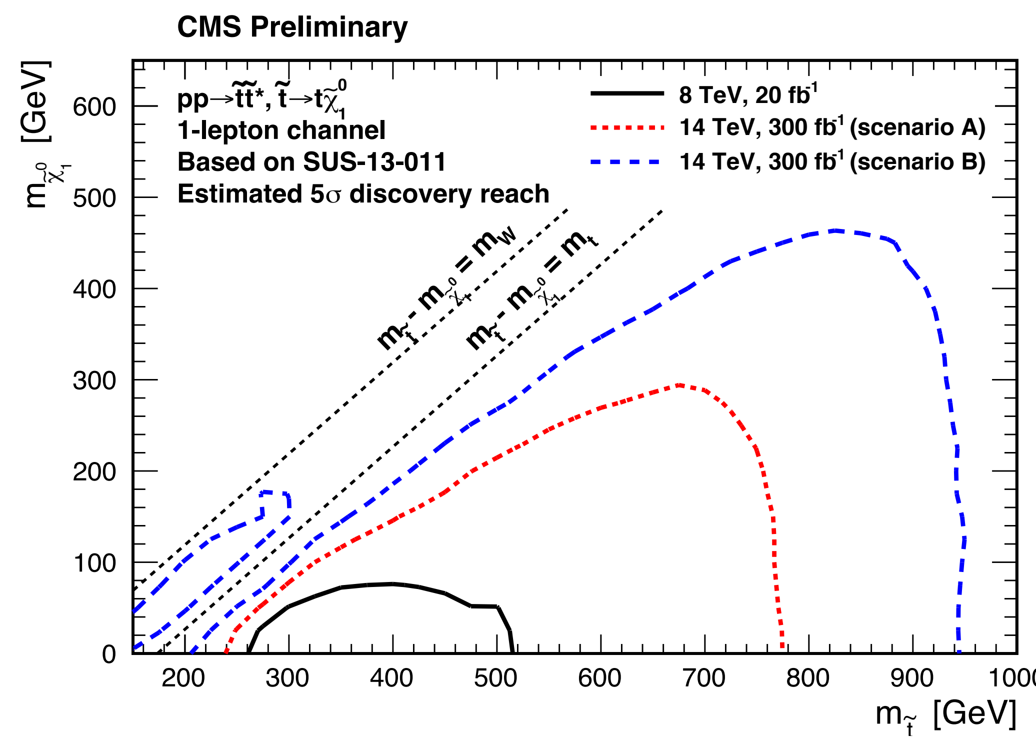
- Not too strong yet (my own opinion).

$$m_h^2 \text{ vs } \frac{3}{8\pi^2} m_{\tilde{t}}^2$$

- We need to go further.

LHC: run 2+



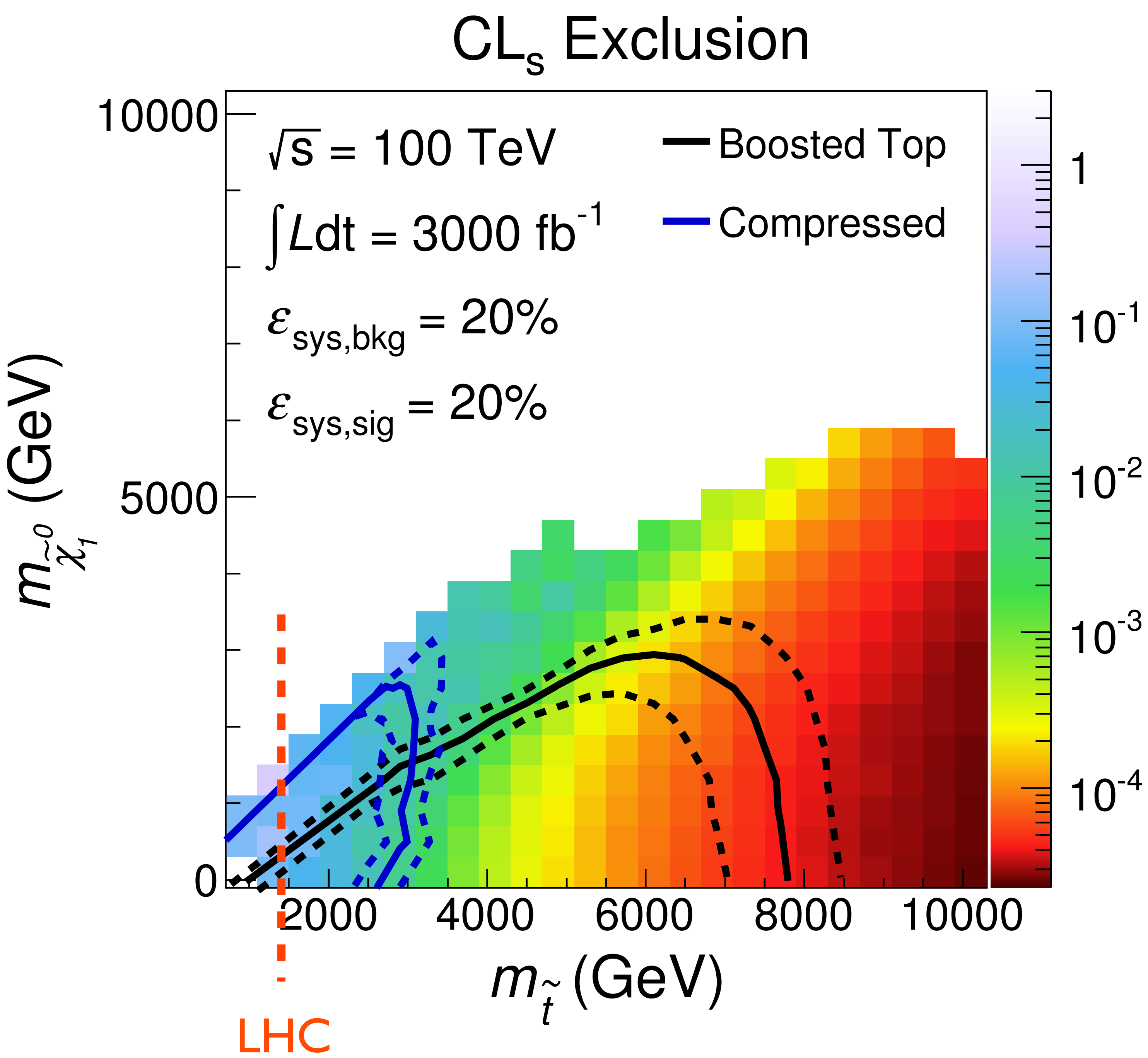


- A big step forward.
- Could discover stop.
- Push up fine-tuning, by a factor of 4.

Fine-tuning $\propto$ m_{stop}^2

At 100 TeV pp collider

Cohen et. al., 2014



A very big step.

Where does this lead us ?

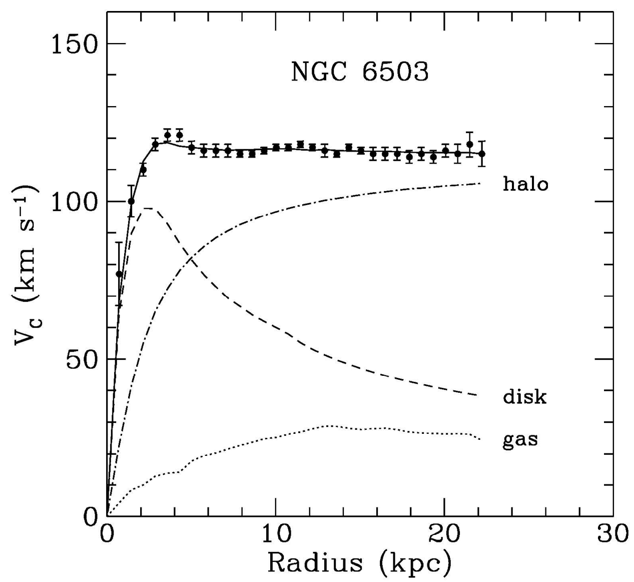
We searched for natural models
Not found yet. We will continue to look

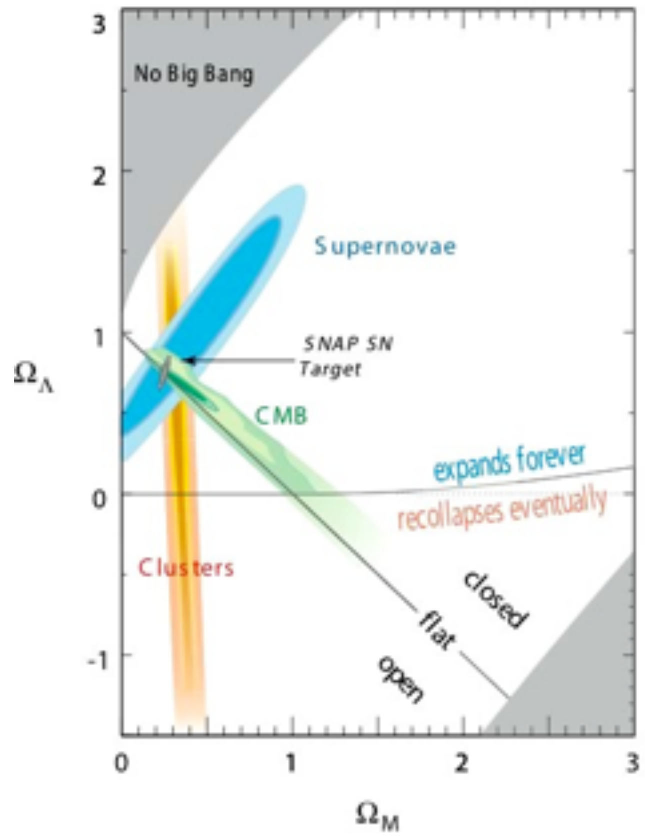
Discover new physics. Triumph (again) for naturalness, and Quantum Field Theory as we know it.

No discovery. Motivation for a big paradigm shift. UV/IR, landscape.... No great idea yet.

Greatest discovery can com from null experimental result.
(Example: Michelson-Morley)

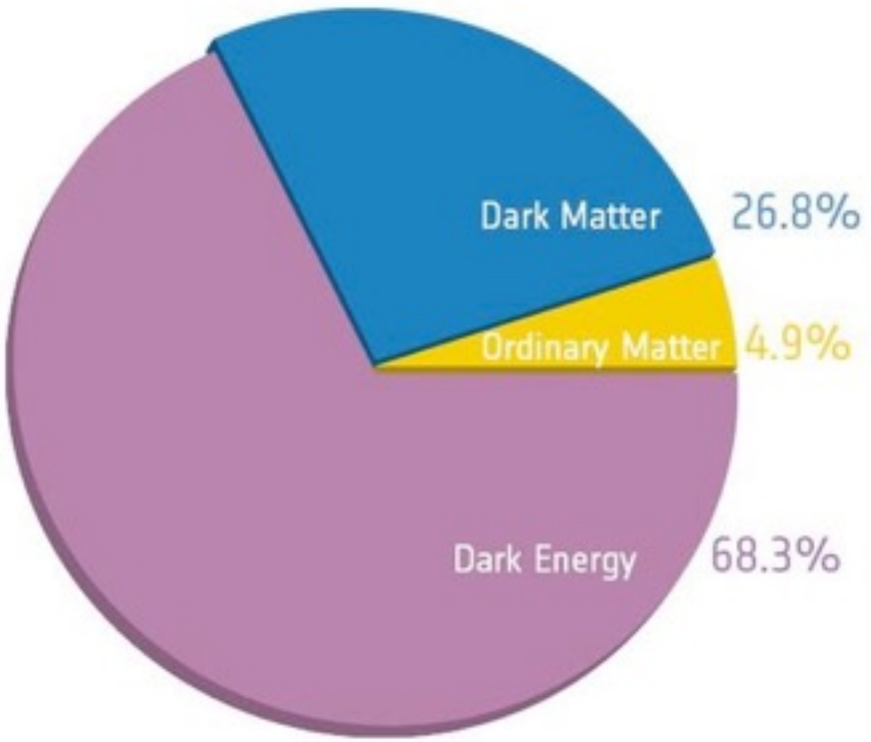
Dark matter



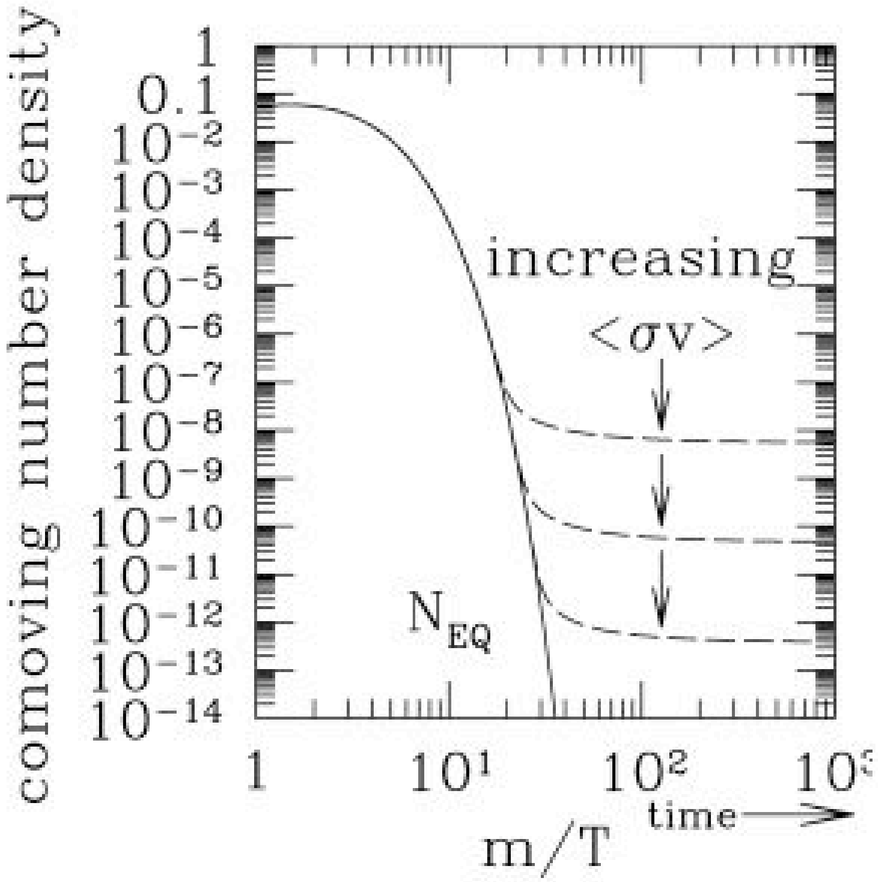


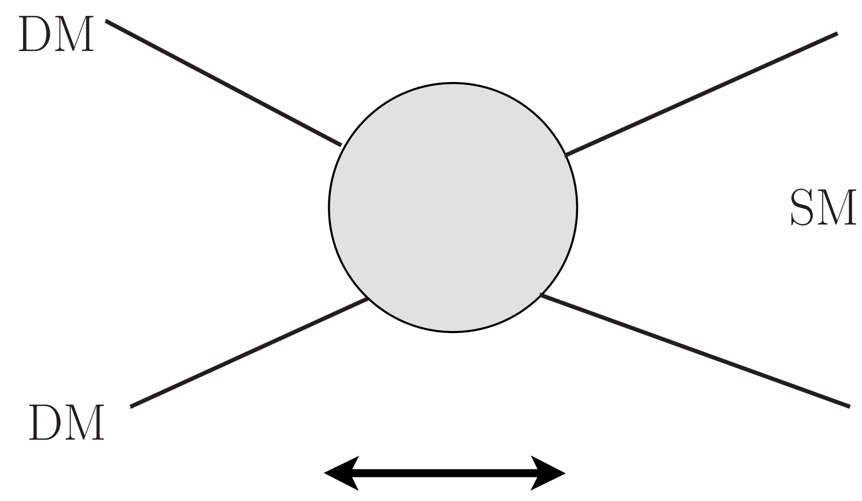
It is there.
Only seen its gravitational interaction.

We have to understand them better.
Collider search is a key approach.



WIMP miracle



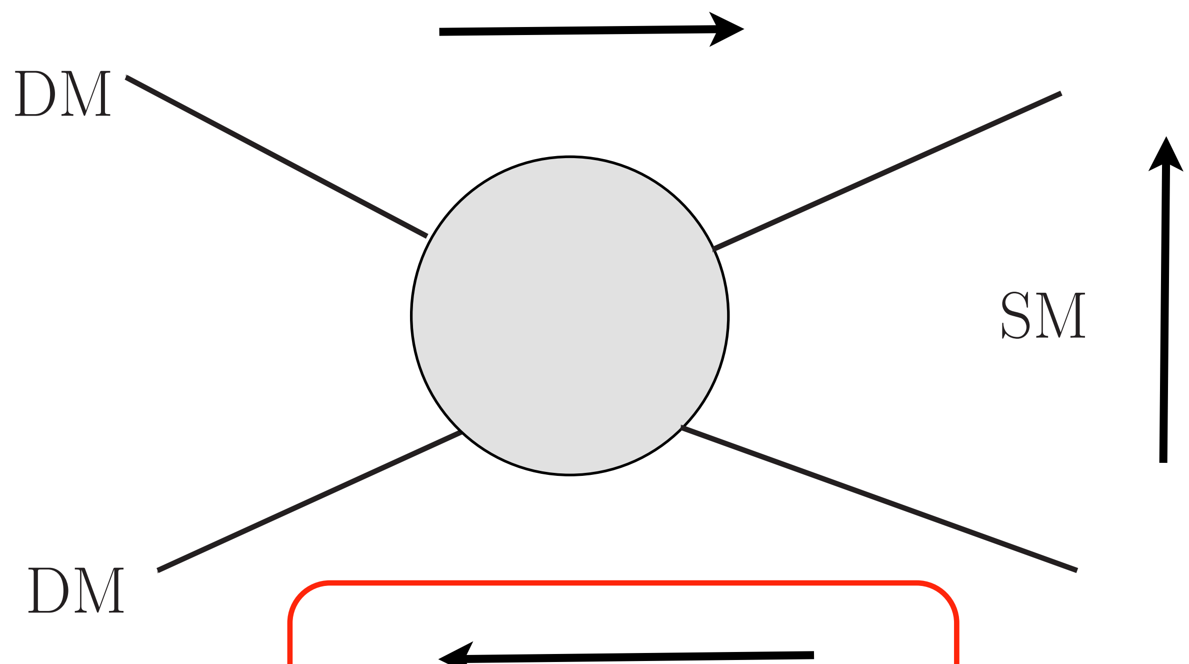


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- Thermal equilibrium in the early universe.
- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- Major hint for weak scale new physics!

Searching for WIMP dark matter

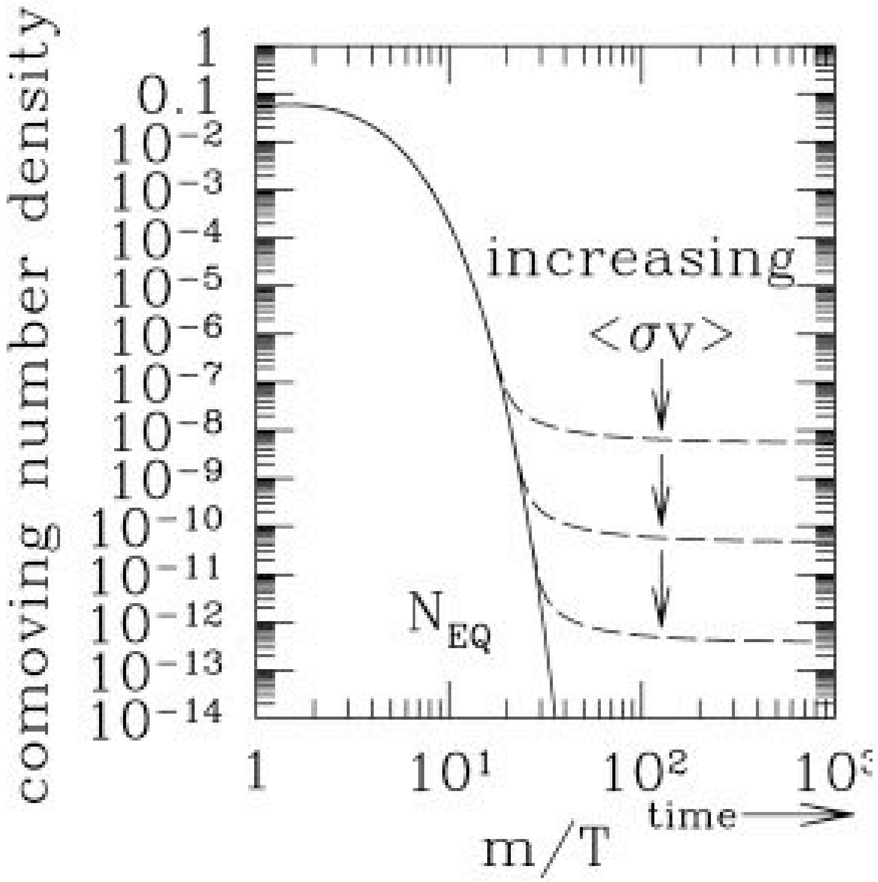
Indirect detection:
AMS2, PAMELA, Fermi-LAT
HAWC, HESS...

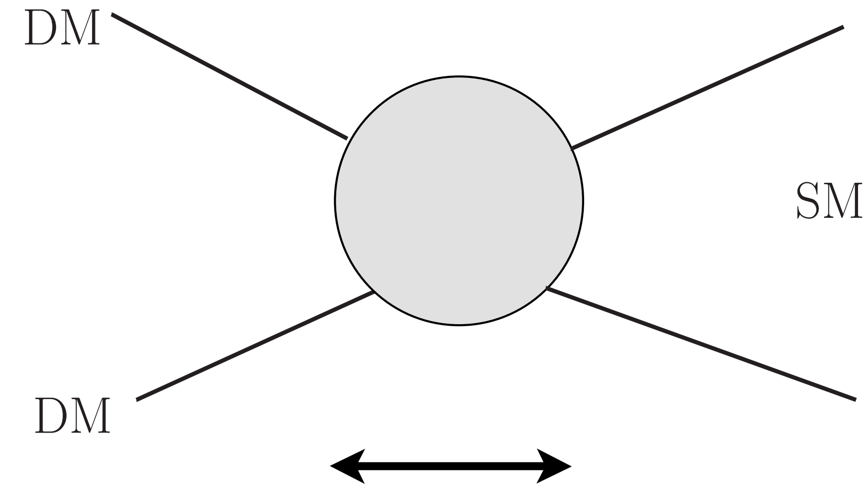


Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON
LZ
.....

Collider searches:
LHC,
100 TeV pp ...

WIMP mass





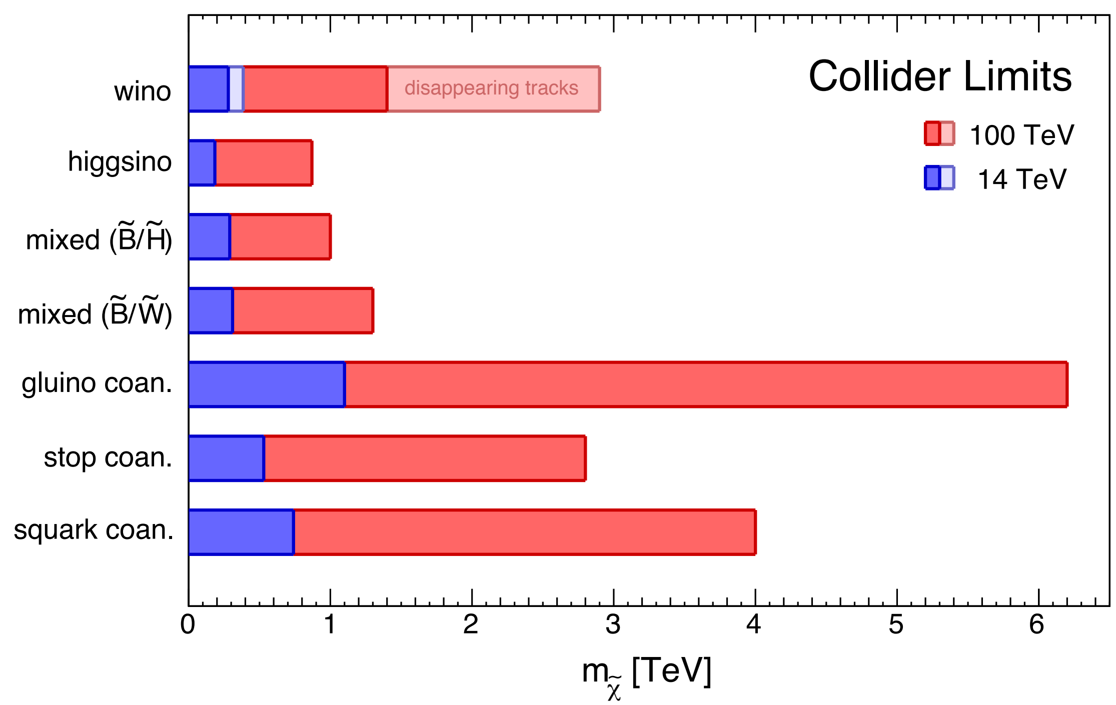
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

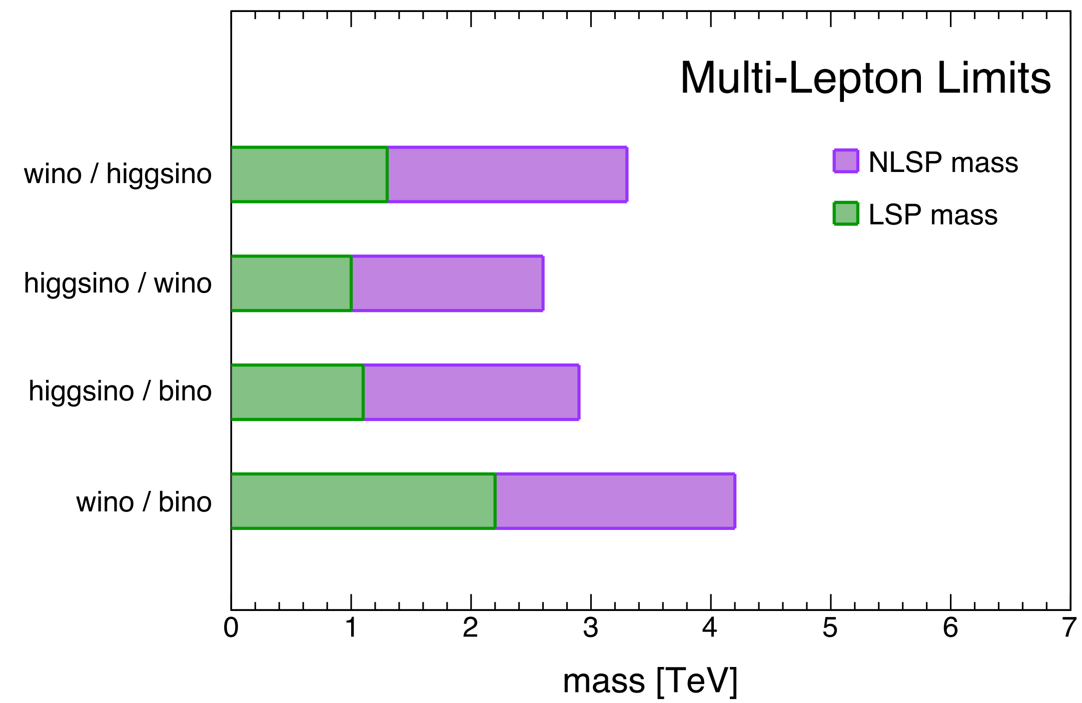
- More precisely, to get the correct relic abundance

$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3} \right)$$

TeV-ish in simplest models

WIMP searches at colliders





$$M_{\rm WIMP} \leq 1.8\ {\rm TeV}\ \left(\frac{g^2}{0.3}\right)$$

Need 100 TeV collider to cover most of the parameter space.

LHC scenarios

No discovery?

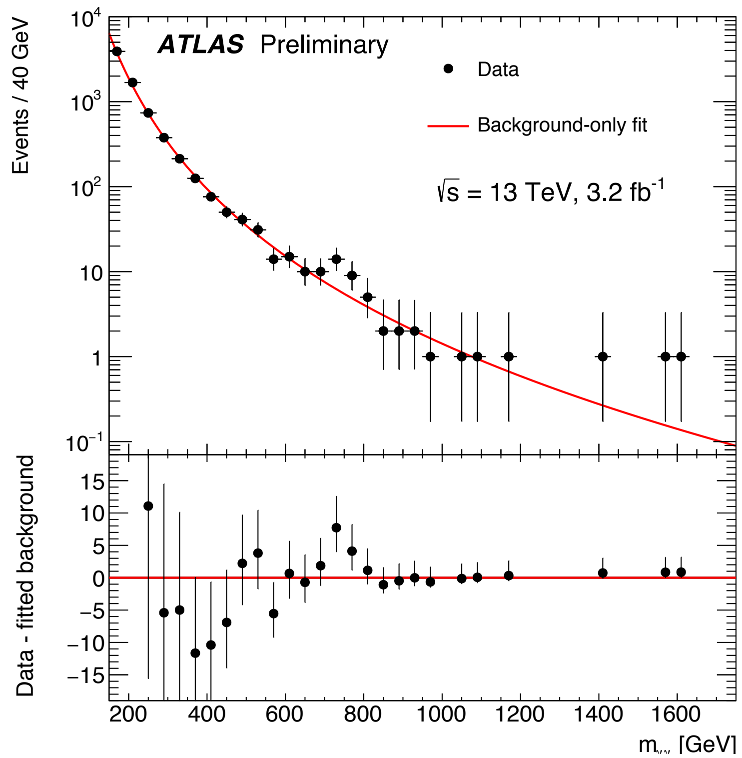
- LHC won't have the final word on many questions.
  - Won't nail the Higgs properties. No complete understanding of EWSB.
  - No good answer for many other questions like for naturalness, identity of dark matter, etc.
- We should certainly go further.

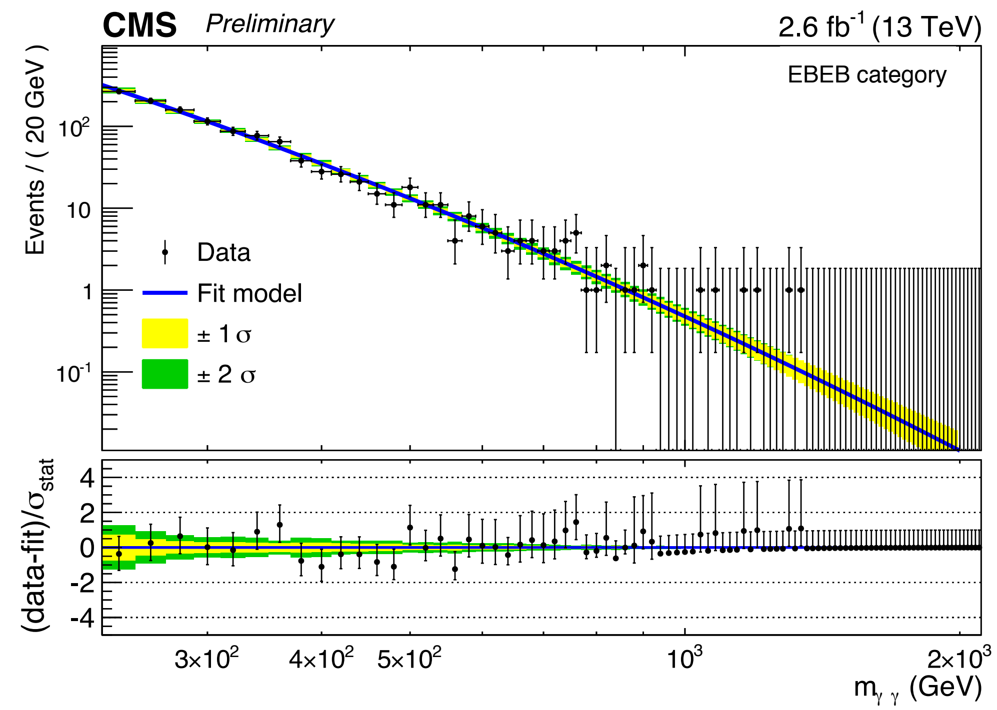
If we make a discovery

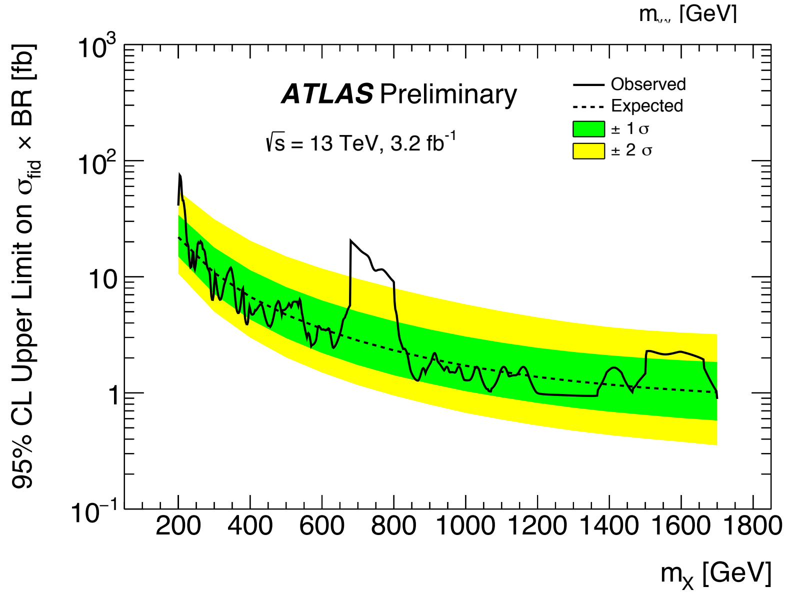
- Beginning of a new era. Seeing the first sign of a new layer of new physics.

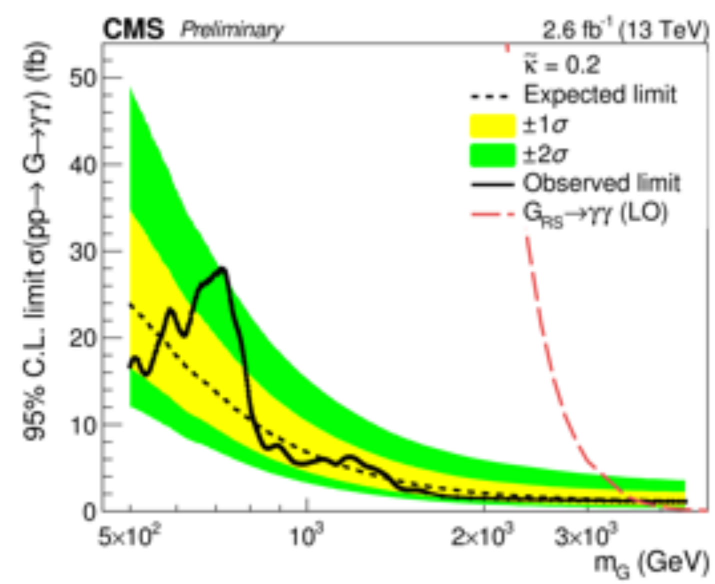
- However, it is unlikely to discover the full set of the particles, since we have not see anything yet.
- Typically, going from 8 TeV to 14 TeV increase the reach at most by a factor of 2.
- However, many models feature particles with masses spread at least factor of several apart.
- Won't be able to see everything.
- LHC discovery will set the stage for our next exploration, in particular at a 100 TeV pp collider.

For example, maybe this one?









$3.6\sigma\,(\text{local})$

$2\sigma\,(\text{global})$

$2.6\sigma\,(\text{local})$

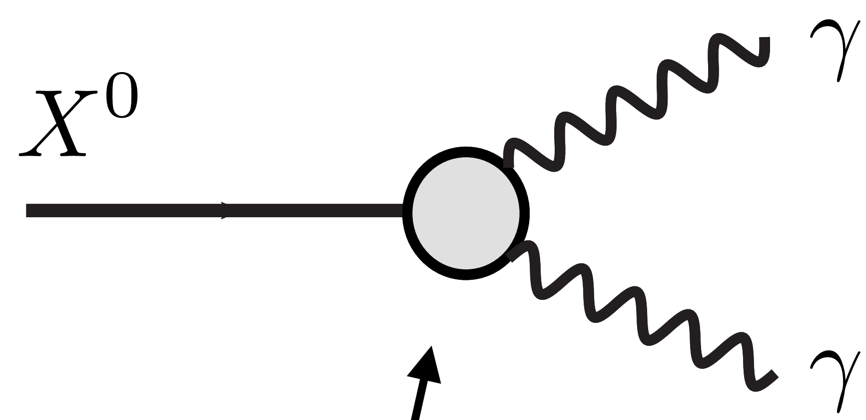
$1.2\sigma\,(\text{global})$

Certainly too early, data in 2016 will tell…

IF

it’s new physics…

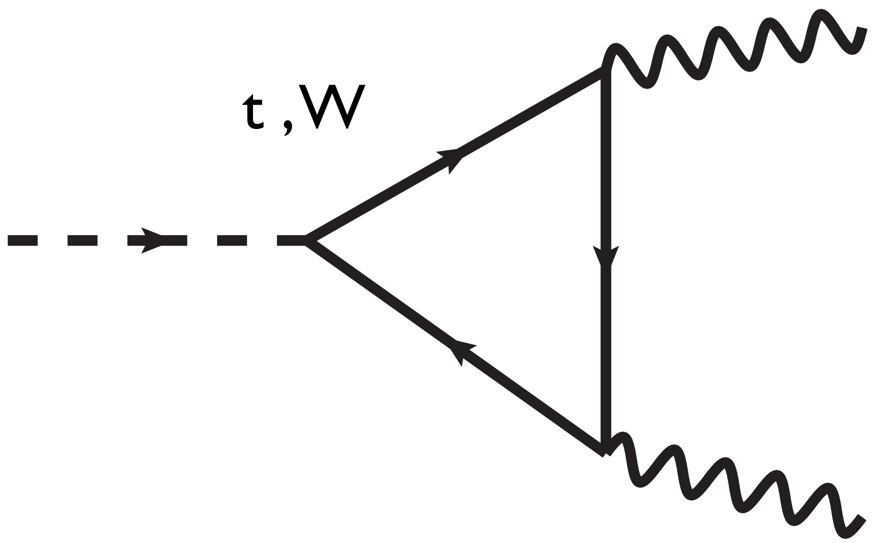
How can neutral particle goes to photon, which only couples to charged particles

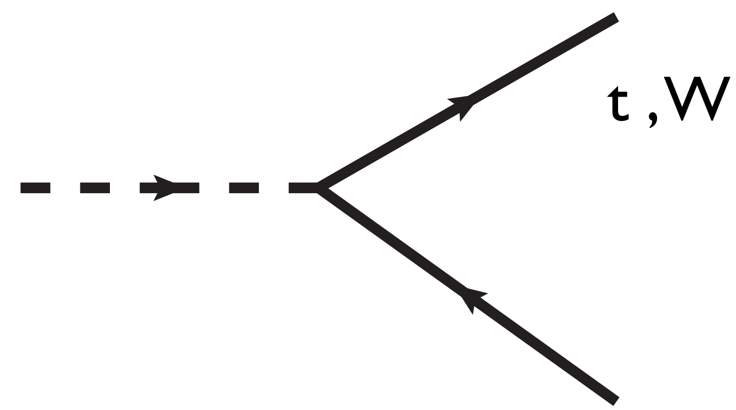


Must be charged particles here.

For the SM higgs, they are top quark and W boson

Can top and/or W do it for the X(750)?





- Say X couples to top and or W, with arbitrary coupling.
  - BR(di-photon) is less than 10^{-4}.
  - 4 fb to di-photon means 10s -100 pb to ttbar and or WW.
  - A factor of 4 or 5 in the production rates between 8 and 13 TeV.
  - ttbar and/or WW signal of at least pb(s) at 8 TeV.
  - Ruled out by run 1 already!

No. Can not (just) be top or W.

750 GeV res. can not be alone.
Must have more new physics!!

Can be the tip of an iceberg.

For example: composite Higgs

Λ=10 TeV : new gluon and quarks

m_* $\approx$TeV(s), resonances

η: 750 GeV

Higgs.

Address the question: why 750 GeV.

IF

it's new physics…

Huge impact on the strategy of future colliders.

Big ring ++

- The motivation for having a very large ring, with the goal of a super proton collider with higher energy (10s to 100 TeV), would be super strong.

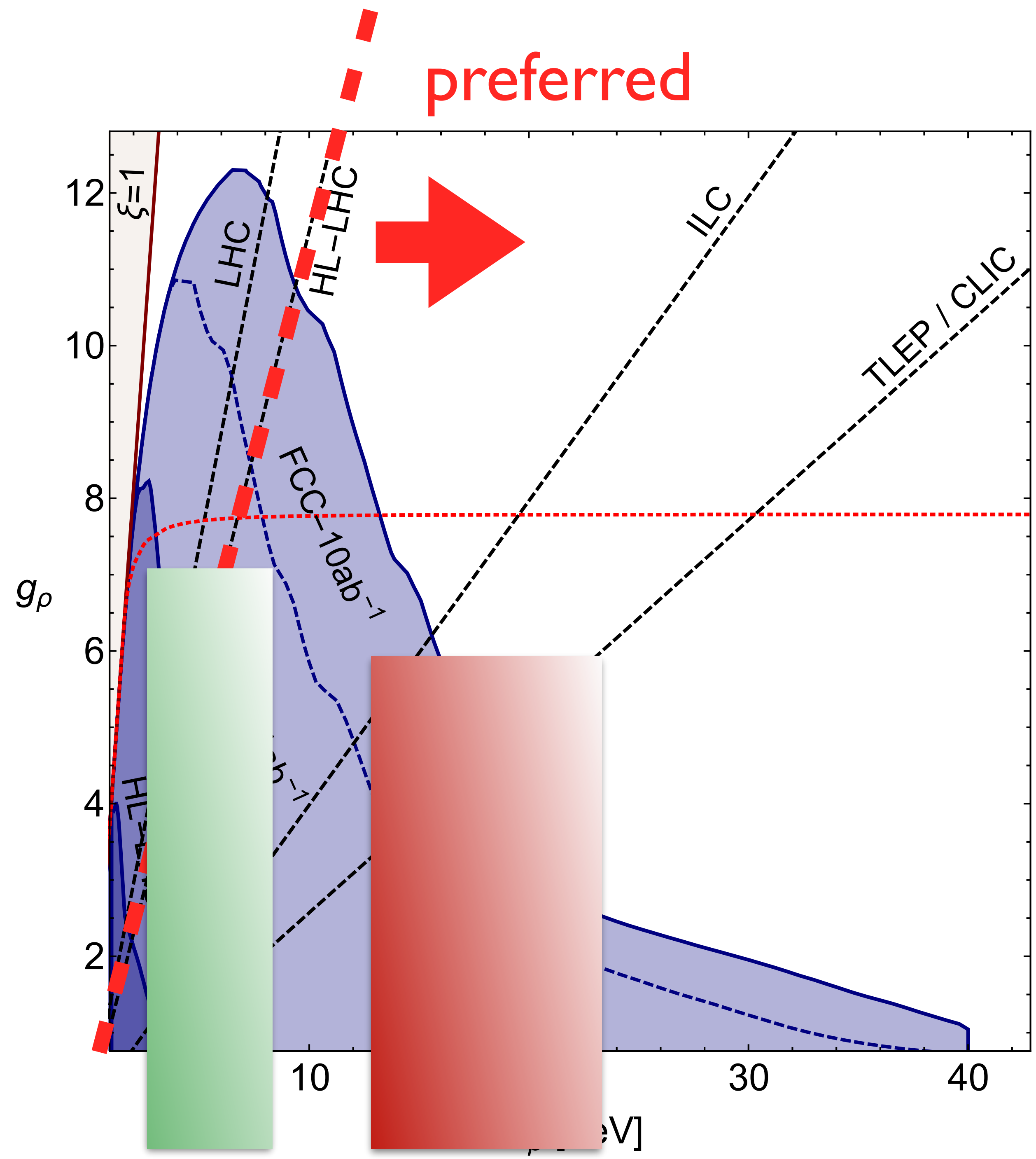
  Completely unravel a new layer of new physics.

  Another 50+ years exciting discoveries.

  Reasonable to have a higgs factory stage.

- Lepton colliders, such as CLIC(to lesser extent the ILC), can cover some ground, especially the new charge particles. But unlikely the full story.

For example: composite Higgs



new resonances

new strong integration new gluon and quarks

What is happening in China?

You probably have heard

China to start work on supercollider by 2020, staking claim as science leader

Guardian

The facility is planned to generate millions of Higgs bosons, far more than the current capacity of the Large Hadron Collider at Cern on the Swiss-French border

The Compact Muon Solenoid, a particle physics detectors built on the Large Hadron Collider at Cern in Switzerland and France. China plans to build a supercollider at least twice as big. Photograph: Rex Features

Well, right direction, not quite there yet.

CEPC-SPPC Timeline (preliminary)

CEPC

2nd Milestone: 13th Five Year Plan R&D

Will know sometime this year

2015 2020 2025 2030 2035

Pre-studies
(2013-2015)

R&D
Engineering Design
(2016-2020)

Construction
(2021-2027)

Data taking
(2028-2035)

1st Milestone: Pre-CDR (by the end of 2014) → R&D funding request to Chinese government in 2015
(China's 13th Five-Year Plan 2016-2020)

Done!

http://cepc.ihep.ac.cn/preCDR/volume.html

SPPC

2020 2030 2040

R&D
(2014-2030)

Engineering Design
(2030-2035)

Construction
(2035-2042)

Data taking
(2042-2055)

CEPC Design –Higgs Parameters

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	240 GeV
Luminosity (peak)	2*10^34/cm^2s
No. of IPs	2

CEPC Design – Z-pole Parameters

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	45.5 GeV
Integrated luminosity (peak)	>1*10^34/cm^2s
No. of IPs	2
Polarization	Consider in the second round

Parameter choice for SPPC (Potential)

(F. Su et al)

Table 4. Parameter lists for LHC HL-LHC HE-LHC FCC-hh and SPPC.

	LHC	HL-LHC	HE-LHC	FCC-hh	SPPC-Pre-CDR	SPPC-54.7Km	SPPC-100Km	SPPC-100Km	SPPC-78Km	
	Value									Unit
Main parameters and geometrical aspects										
Beam energy[E_0]	7	7	16.5	50	35.6	35.0	50.0	68.0	50.0	TeV
Circumference[C_0]	26.7	26.7	26.7	100(83)	54.7	54.7	100	100	78	km
Lorentz gamma[γ]	7463	7463	14392	53305	37942	37313	53305	72495	53305	
Dipole field[B]	8.33	8.33	20	16(20)	20	19.69	14.73	20.03	19.49	T
Dipole curvature radius[ρ]	2801	2801	2250	10416 (8333.3)	5928	5922.6	11315.9	11315.9	8549.8	m
Bunch filling factor[f_2]	0.78	0.78	0.63	0.79	0.8	0.8	0.8	0.8	0.8	
Arc filling factor[f_1]	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	
Total dipole magnet length [L_{Dipole}]	17599	17599	14062	65412 (52333)	37246	37213	71100	71100	53720	m
Arc length[L_{ARC}]	22476	22476	22476	83200 (66200)	47146	47105	90000	90000	68000	m
Total straight section length[L_{ss}]	4224	4224	4224	16800	7554	7595	10000	10000	10000	m
Energy gain factor in collider rings	15.6	15.6	13.5	15.2	17.0	16.67	17.5	17.5	17.5	
Injection energy [E_{inj}]	0.45	0.45	>1.0	3.3	2.1	2.1	2.9	3.9	2.9	TeV
Number of IPs[N_{IP}]	4	2	2	2	2	2	2	2	2	

In 2016

- We will know whether China will start support R&D work (13th 5 year plan, or through some other means).

- Will produce a CDR.

  More detailed CEPC design, more specific choices (size of the ring etc.).

  More detailed physics argument to support the design choices.

- Aggressive effort in seeking international support, building collaboration.

More opportunities and challenges

- Better SM theory calculation needed for taking full advantage of energy and luminosity.
- Many more NP channels, e.g. flavor (violating) physics at 10s TeV?
- Full set of Higgs measurements at 100 TeV, both inclusive and energy dependence.
- Physics driven (such as dark matter search) novel detector designs.
- We will and should do much better than we know now in a couple of decades. cf. LHC vs SppS.

Conclusions

- Higgs discovery "completes" SM. LHC will further extend our reach in new physics.
- Several fundamental questions in particle physics will not be answered (fully) by the LHC.
  - Understanding EWSB, naturalness, dark matter, etc.
- Going beyond the LHC, circular colliders
  - Higgs factory + high energy pp collider.
  - Many activities, particularly the last couple of years.
  - Great physics case.
  - Effort underway to make it happen.

A lot to look forward to...